THE ACOUSTIC RAMP:
AN ANALYSIS OF DIFFUSER TESTING METHODOLOGIES

BY

HENDRIK DAVID GIDEONSE XIX

ABSTRACT OF A THESIS SUBMITTED TO THE FACULTY OF THE
DEPARTMENT OF MUSIC: SOUND RECORDING TECHNOLOGY
IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR THE DEGREE
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DEDICATION

This academic work is dedicated to the teachers who have inspired me the most:

Debbie Ray

Joseph Yoshimura

Joe Lewis

Wylie Ferguson

John McDonald

Katherine Bergeron

William Moylan

Alex Case

And to my family who will really enjoy that this project is finally over:

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ABSTRACT TITLE PAGE

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ABSTRACT

The Acoustic Ramp is a wedge-shaped, number-theoretical quadratic-residue-type acoustic diffuser. Since the late 1970's, several methodologies for the testing and analysis of diffusers have been developed including, the ISO Scattering Coefficient and the AES Diffusion Coefficient. These coefficients are the source of some controversy today and this paper makes the attempt to investigate the benefits and weaknesses of these tools by using them to research and test the Acoustic Ramp. Several issues are exposed in using the coefficients, the most important of which being the validity of the comparison of the diffuser's behavior to that of a like sized flat panel. Further issues comprise of an intuitive disconnect between the perceived merits of polar plots and the numerical value of coefficients derived from the plots.

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INTRODUCTION

The idea for this project took shape during the University of Massachusetts Lowell course called Advanced Acoustics for Audio, taught by Alex Case. The class was studying acoustic treatments and in particular the quadratic residue diffusers (QRDs) conceived of by Manfred Schroeder. It was clear that the relationship between the depth and width of the wells of the diffusers and their effective bandwidth was the biggest limitation of traditional rectilinear QRDs[1]. The variation of the well-depth was seen as an opportunity for the improvement of the design. Deep diffusive treatments do effectively address lower frequencies, but also use up much valuable floor space, particularly in small rooms. For example, a 10' x 10' room is 100 square feet. 6" of absorption and diffusion around the perimeter shrinks the room to 9' x 9' which is only 81 square feet. This is a loss of nearly 20% of the usable floor space.

The goal was to develop an effective, wide-bandwidth diffuser that would conserve as much floor space as possible. The idea for the Acoustic Ramp was born of the desire to shrink the depth of the bottom of a standard QRD, while maintaining the mathematical relationships between the well depths. This idea prompted the creation of a wedge-shaped diffuser with the tapered end pointing downwards, and mounted at the intersection of the wall and ceiling. This configuration allowed for furniture or other objects to be pushed against the wall beneath the acoustic treatment, but maintained the required depth to diffuse lower frequencies.

There are several benefits that resulted from the alteration of the traditional QRD design. First, the wedge shape of the treatment causes the depth of the wells to be continuously variable from a maximum depth to zero depth, which widens the effective bandwidth of the diffuser. Second, the rear walls of the wells, called reflectors, are no longer parallel to the wall on which the diffuser is hung. Therefore, when used in a room with parallel walls, the Ramp "de-parallels" the walls, redirecting reflected energy away from the opposing wall, reducing flutter echo and other negative acoustic properties. Third, the wedge-shape allows the acoustician to direct reflected energy in a specific direction. The reflectors are not all parallel to each other either, so the reflected energy is spread across several angles increasing the complexity of the scattering behavior.

The development of the Acoustic Ramp has taken place over several years and includes the iterative construction of multiple prototypes in different materials, the drafting of both provisional and non-provisional patent applications[2], and several attempts at quantifying the diffusion properties of the invention. The most academically relevant parts of the development process are the initial designs and testing of the Ramp in its most basic form, which is roughly 2 feet wide, 4 feet tall and 1 foot deep, using the quadratic residue sequence based on the prime number 7. The testing methodology will be discussed, analyzed and evaluated.

One of the particular challenges in testing diffusion is the reduction of the collection of extremely complex data into an intuitive and consistent coefficient. While it was hoped that the controversy of evaluating the value and validity of the Autocorrelation

Diffusion Coefficient, the Normalized Diffusion Coefficient, and the ISO Scattering Coefficient could be avoided, it was found to be impossible. It is clearly best to evaluate the actual raw data in the form of sonograms or a series of polar distribution plots, but these graphical displays are unwieldy and lack the simplicity of a single number. Some sort of reduction of complexity is needed both to provide a vocabulary for succinctly discussing diffusion properties and to allow the comparison of diffusive treatments and products.

As absorption and the Absorption Coefficient have been studied for much longer than their diffusion counterparts, they tend to be much less controversial. They are still of course being fine tuned as new information is discovered and integrated into the bulk of research.[3] The Scattering Coefficient, being close to the inverse of the absorption coefficient, has gained authority by association with its absorbent cousin. The Scattering Coefficient is a useful comparison between bumpy scattering surfaces and flat planar surfaces or the same size. This coefficient is derived by comparing the quantity of energy in the specular zone, where a flat panel's reflection lives, to the energy in the non-specular zone.

The Diffusion Coefficient (d_ψ) and the accompanying Normalized Diffusion Coefficient obtained using the autocorrelation formula as described in AES-4id-2001 [4] are not very satisfying. The intent of their creation was to create a qualitative measure allowing the comparison of different diffuser shapes. The Diffusion Coefficient does seem to be excellent at identifying both perfect diffusers and perfect acoustic focusers very well. It also does a reasonably good job of showing the functional bandwidth of a given diffuser. However, it does not excel at comparisons of the quality or effectiveness of typical diffusers.

The acoustics community requires a metric for evaluating, discussing and comparing diffusive behavior that is intuitively consistent with the apparent reflective directivity shown by polar distribution plots. There are two obstructions to obtaining a truly useful diffusion coefficient that are examined in detail in the DISCUSSIONS section:

1. The comparison of the diffuser to a flat panel of the same size
2. The difficulty of the search for a formula that generates a coefficient consistent with the intuitive understanding of good diffusion patterns

Background: Acoustic Diffusion

In the field of Acoustics, there exist only three commonly-accepted means of changing acoustic behavior with treatments: absorption, reflection, and diffusion.[1]

1. Absorption, the most well understood technique, is the process in which acoustic energy comes in contact with a material that converts the energy into heat, preventing subsequent reflection.
2. Reflection is the process in which acoustic energy strikes a material and is redirected largely unchanged. The angle of incidence of the sound source relative to the reflector is equal to the angle of reflection. In this way, sound behaves similarly to a rubber ball striking a hard flat surface. Lower frequencies tend to act like waves and higher frequencies tend to behave like light rays. Reflections from flat surfaces are called specular reflections.
3. Diffusion is the process in which acoustic energy is scattered and distributed evenly after it comes in contact with a rigid, non-uniform shape with lots of surface area.

Diffusion redirects and spreads acoustic energy over a larger area than a specular reflection, where energy is concentrated into a narrow pattern. Diffusion decreases the reflected energy in the specular zone by redistributing the energy to other locations. When a sound strikes a surface that is uneven, non-uniform and with a varied texture, the energy does not contact the surfaces all at the same time. The resulting reflections return with small changes in timing or phase. A good diffuser causes both scattering, creating reflections in many directions, and changes in phase, creating reflections at several times. One measure of diffusion involves examining how an impulse of acoustic energy is smeared or spread out over an amount of time.

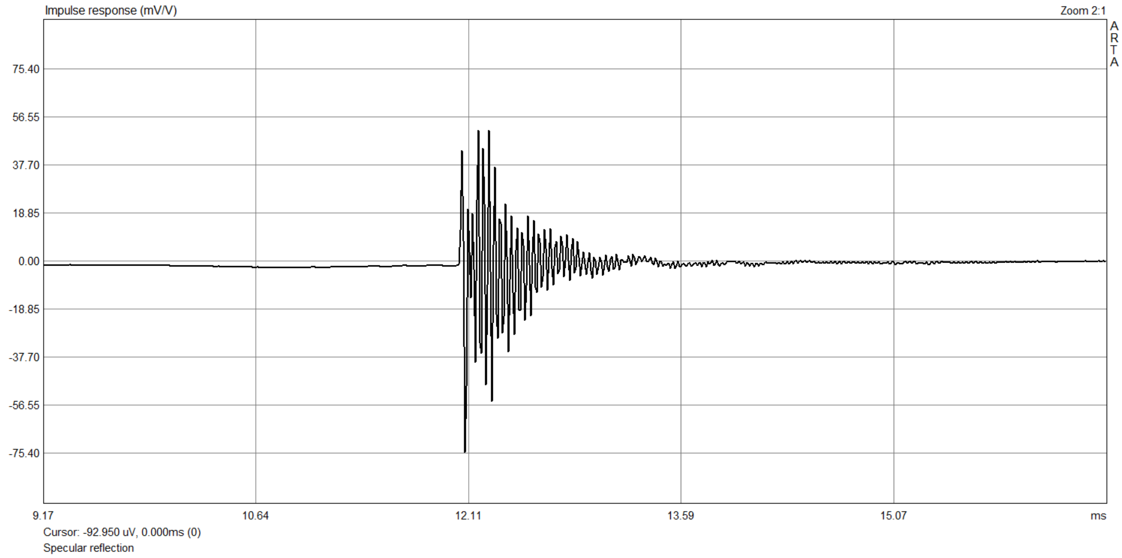


Figure 1 Specular reflection from a flat panel

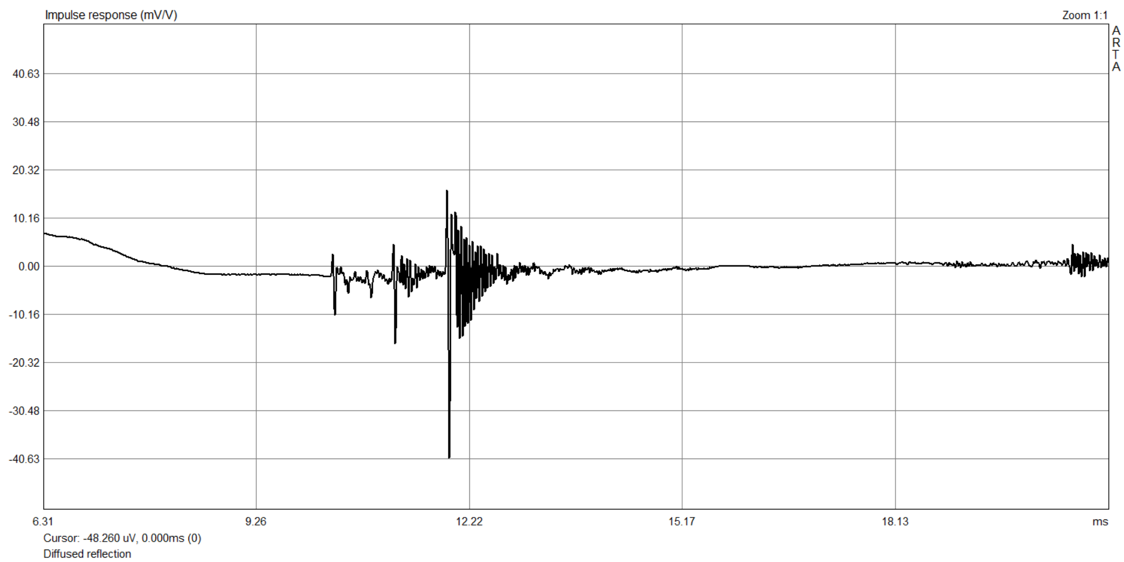


Figure 2 Time variation from diffuser treatment

The concert halls of the 18th and 19th centuries all possessed many irregular surfaces. Diffusion was built into the architecture through, for example, recessed alcoves with sculptures and highly articulated and ornamented moldings and coffers. As construction materials and techniques have evolved, the problem in contemporary acoustics is to find diffusive shapes that are easier and cheaper to manufacture than hand carved moldings and marble sculpture.

Diffusers are considered to be either one dimensional or two dimensional. Sound striking a single-dimensional or 1D diffuser would be diffused in a semi-circular pattern away from the diffuser in a single plane. A two-dimensional or 2D diffuser would diffuse sound in a hemispherical pattern, both horizontally and vertically. Additional information about defining and evaluating diffusion is in the section Defining Diffusion.

What Do We Really Want a Diffuser to Do?

The better a diffuser distributes reflected acoustic energy in all directions, the better the diffuser is. Ideally all frequencies would scatter equally in all directions. Unfortunately, this is quite a difficult task. It becomes very hard to diffuse low frequencies because long wavelengths require very large acoustic treatments. High frequencies are also somewhat difficult because of the intricacy of construction required for very small frequency scattering and because higher frequencies tend to be absorbed by all but the hardest materials. Most diffusers work almost exclusively in the midrange from 500 to 5000Hz and largely these diffusers have satisfied most of the requirements and expectations of their users. It is in this spirit that I am hoping to create a list of what most people need and expect from their diffusers. This is necessarily looking at the science behind what a diffuser does to reflected energy, how this behavior interacts with actual rooms that people live and work in, and also the psychoacoustic effects on the people in the rooms. The following is a list of typical diffuser uses:

1. To control rear wall reflections

   Diffusive treatments are used to prevent the rear wall from reflecting directly back to the listener and the sound source, but without excessively reducing the amount of acoustic energy in the room. In practice, the majority of diffusive treatments are reserved for the rear wall of critical listening spaces, like the control room of a recording studio, because diffusion is usually the most expensive acoustic treatment and can only be used in a limited capacity.

2. To control comb filtering

   Comb filtering occurs when reflected sound is similar to and interferes with the direct sound. The time delay between the two causes boosts and cuts in certain frequencies which changes the tone or timbre of the sound. Comb filtering is particularly problematic in smaller rooms where the walls are always relatively close to the listener.

3. To control flutter echo

   Flutter echoes are rapid repeating echoes following a direct sound. Very often the echo has resonant frequencies that create a ringing sound. Flutter echo is often associated with parallel reflective walls and is the most easily recognizable problem in acoustic spaces.

4. To disrupt room modes

   All rooms have room modes, where there are noticeable resonant and null locations for specific frequencies particularly below 250 Hz. The frequency of the most noticeable modes are a function of the length, width and height of the room. Parallel walls emphasize problems with nodes because sounds that have wavelengths that are equal to multiples of the dimensions of the room are particularly likely to become resonant..

5. To increase size of the so-called sweet spot and flatten the frequency response of other areas of the room

   The sweet spot is the location where a listener places their head to be as sonically accurate as possible. This is the location where the listener is equidistant from each loudspeaker in a stereo listening environment where the speakers are 60 degrees apart. A small sweet spot is noticeable because small head movements make large changes to the sonic landscape. A larger sweet spot allows the listener to move their head without causing major changes to the listening experience.

Background: Schroeder's Number Theoretical Diffusers

Manfred R. Schroeder is the father of modern acoustic diffusion research. Most diffusers designed and manufactured today are at least partially based on his ground-breaking research. He was the first scholar to explore the use of rectilinear wells of different depths as a means of diffusing acoustic energy.[5] Schroeder applied the idea of the light and x-ray scattering properties of crystals to the scattering of acoustic energy. The concept of this type of diffusion is called reflection phase grating.[6]

Schroeder's one-dimensional diffusers consist of a series of rectilinear wells each with the same height and width, but with varying depths. The depths of the wells determine the lowest frequency scattered by the diffuser. Specifically, when the depth of the well is equivalent to a quarter of the wavelength (or more), phase shifts of 90 degrees (or more) are achieved, leading to diffusion.[5] Manfred Schroeder's work on number theoretical acoustic diffusers gives us the following low frequency, quarter wavelength limit for diffusion based on well depth:

$$Lowest\ Diffused\ Frequency\ (Hz) \approx \frac{Speed\ of\ Sound}{4 * (Depth\ of\ Deepest\ Well)} \tag{1}$$

Formula 1[6]

The width of the wells determine the highest frequency diffused. A surface is considered a reflector when its size greater than the wavelength of interest. Sound is diffracted when the surface is smaller than the wavelength. Keeping the width of the well to one-half wavelength or less gives the following upper frequency limit based on well width:

$$Highest\ Diffused\ Frequency\ (Hz) \approx \frac{Speed\ of\ Sound}{2 * (Width\ of\ Wells)} \tag{2}$$

Formula 2 [6]

The figure below shows an elevation of a Quadratic Residue sequence of depths based on prime number 7. The number sequence determines the ratio of depths of the wells of the diffuser.

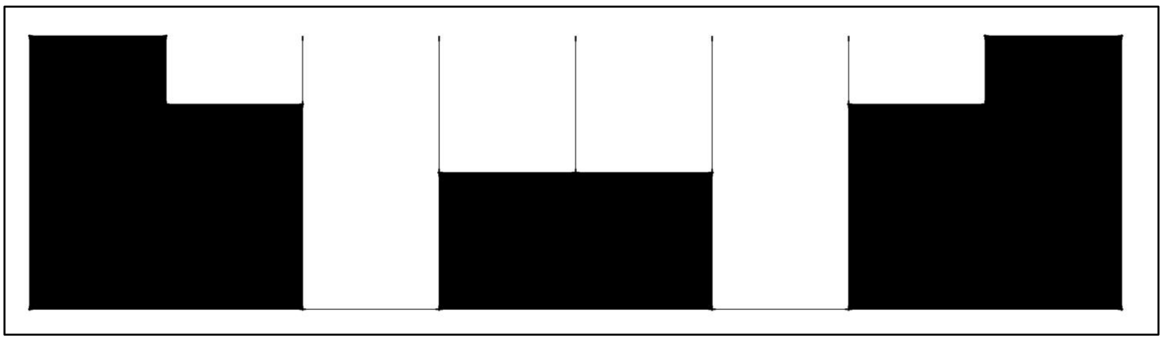


Figure 3 Elevation of prime number 7 quadratic-residue based well depths

Schroeder used both Quadratic Residue (QR) and Primitive Root (PR) number sequences to obtain semi-random number sequences to determine the depths of the wells.[6] Quadratic Residue Sequences are obtained in the following manner:

1. ***p*** = any prime number (e.g. 11)
2. for every integer (***n***) from 0 to ***p*** do the following:

   find the remainder from $\boldsymbol{n^2/p}$ (e.g. $1^2/11$ = 0 Remainder **1**)

   This can be written mathematically as:

   $\boldsymbol{n^2}$ **modulo *p***

   The remainder is the number in the number in the quadratic residue sequence.

Examples of other Quadratic-Residue Sequences with the prime number from which they are derived:

p = *5:* 0 1 4 4 1 0

p = *7:* 0 1 4 2 2 4 1 0

p = *11:* 0 1 4 9 5 3 3 5 9 4 1 0

p = *13:* 0 1 4 9 3 12 10 10 12 3 9 4 1 0

p = *17:* 0 1 4 9 16 8 2 15 13 13 15 2 8 16 9 4 1 0

p = *19:* 0 1 4 9 16 16 6 17 11 7 5 5 7 11 17 6 16 9 4 1 0

p = *23:* 0 1 4 9 16 2 13 3 18 12 8 6 6 8 12 18 3 13 2 16 9 4 1 0

The most basic form of a Quadratic Residue Diffuser based on prime=7 is shown in Figure 4 below.

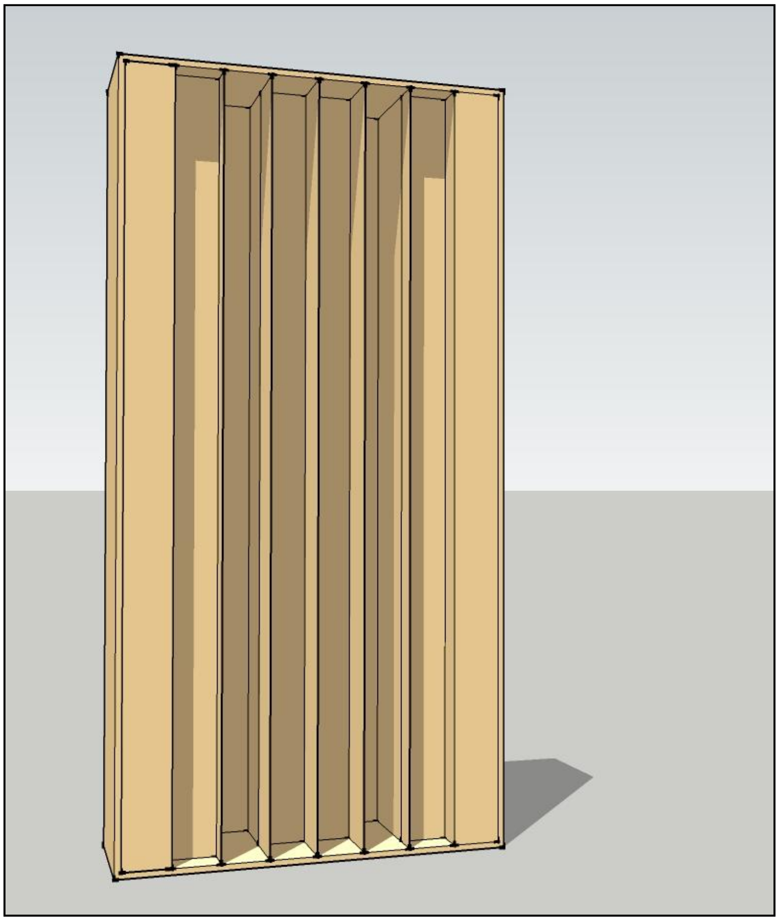


Figure 4 Standard Quadratic Residue Diffuser (QRD)

The diffuser pictured above is what is called a one-dimension diffuser, meaning that sound reflecting from the diffuser is spread in a semicircular pattern in a single plane as shown in Figure 5.

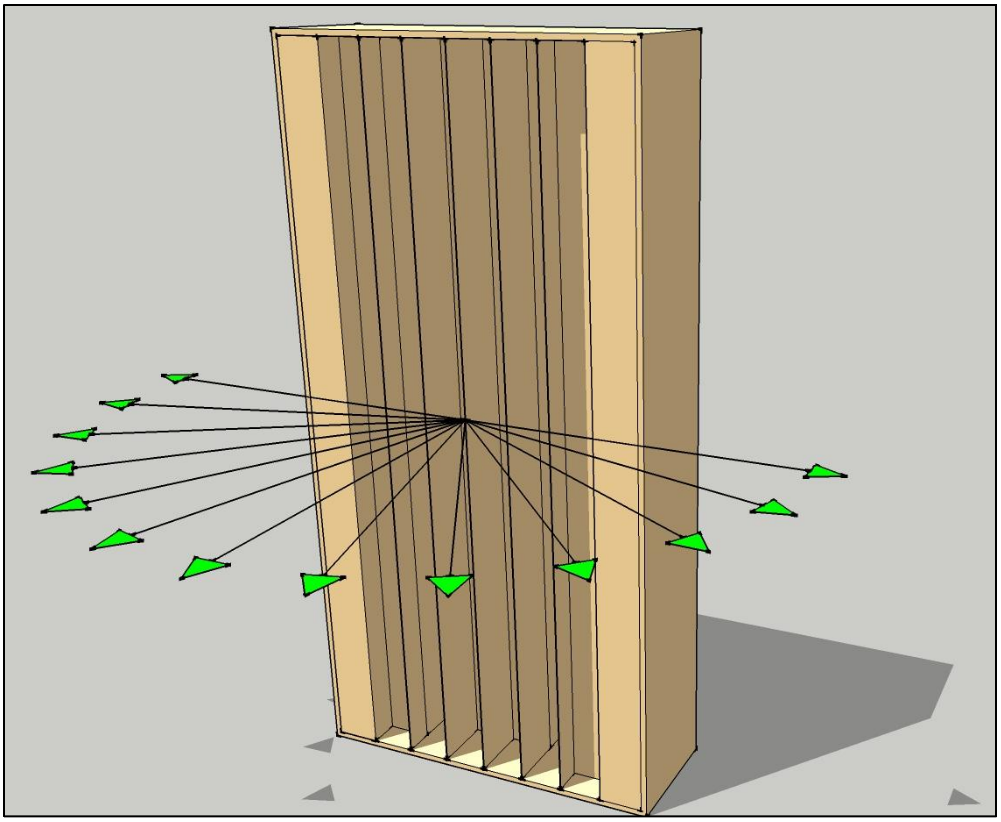


Figure 5 Standard QRD's scatter (green arrows) energy in a semicircular pattern

Schroeder also experimented with two-dimensional diffusers similar to the commercial products like RPG, Inc's Hemifussor and Skyline diffusers depicted below:

Figure 6 The Skyline Primitive Root 2-Dimensional Diffuser by RPG Inc. [7]

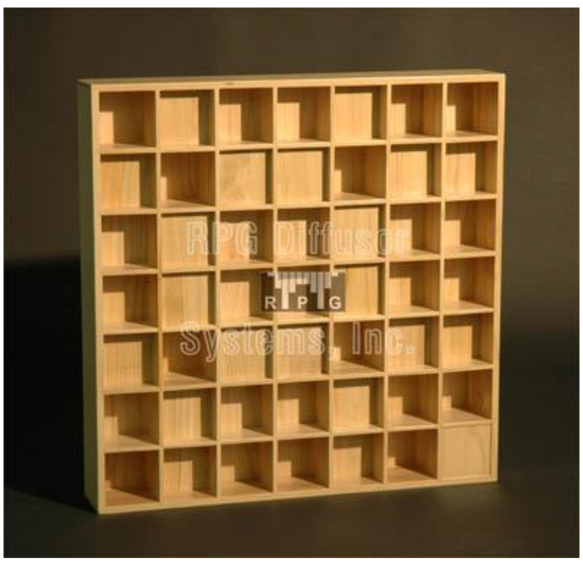


Figure 7 The Hemiffusor W1 by RPG Inc. [8]

Both the Skyline and Hemiffusor diffusers scatter sound in a hemispherical pattern [4] in two dimensions. 1-Dimensional diffusers are often used in arrays where both vertical and horizontal configurations are used together to increase the hemispherical nature of the performance of the diffusers, like in Figure 8.

Figure 8 The QRD 734 by RPG, Inc used in an array of both vertical and horizontal orientations. [9]

What Is the Acoustic Ramp?

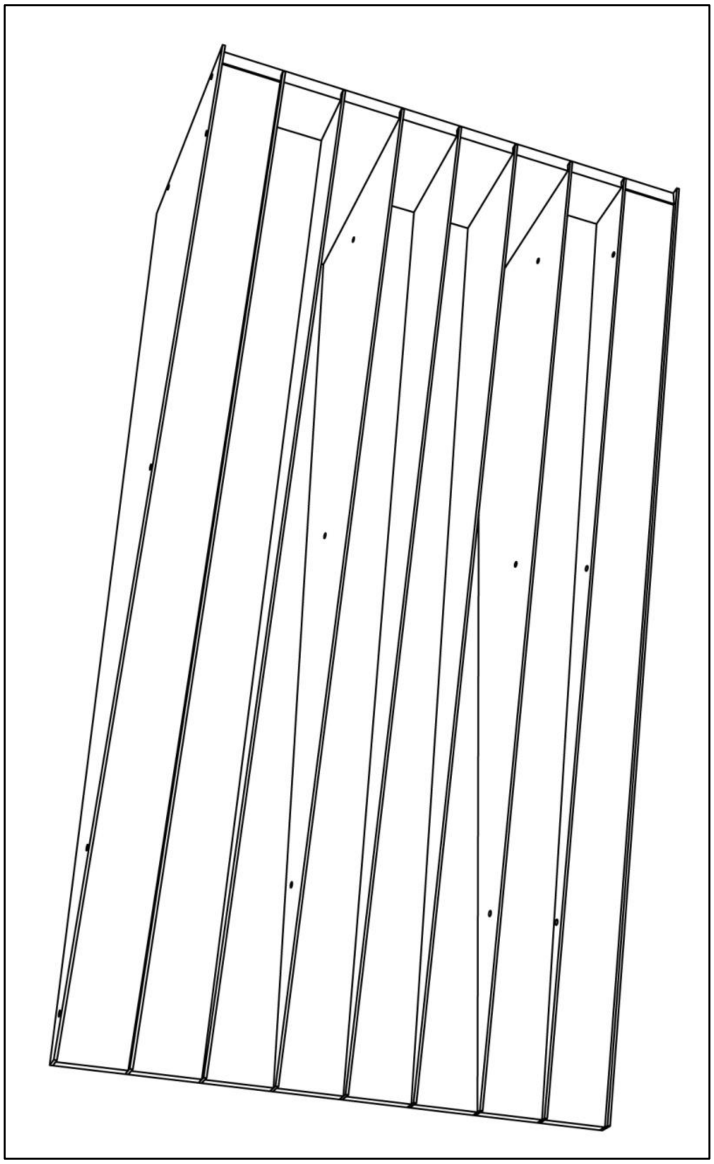


Figure 9 Commercial Version of the Acoustic Ramp

The Acoustic Ramp is a wedge-shaped quadratic residue diffuser that is based on the designs of Manfred Schroeder. It is intended to be permanently mounted on walls or ceilings or mounted temporarily on speaker stands. It is especially useful when mounted along the wall/ceiling interface with the wedge shape pointing down. The Ramp scatters acoustic energy in a semi-circular pattern in one dimension (see Figure 10 below) and provides scattering in a quarter circular pattern in the other dimension.

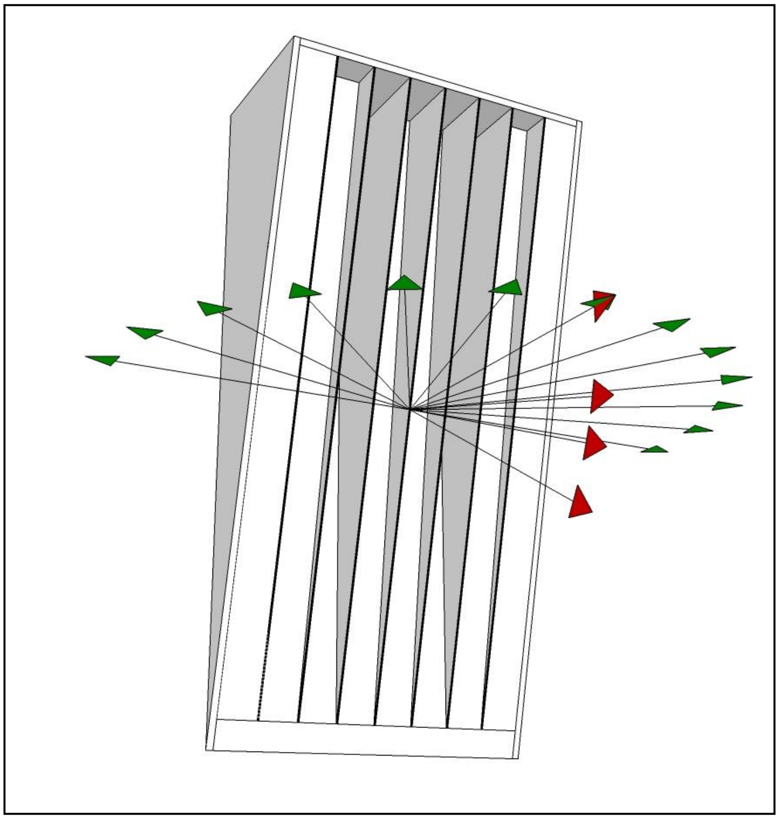


Figure 10 The Acoustic Ramp Both Scatters (green arrows) and Reflects (red arrows) Energy.

The wedge shape of the diffuser also provides another function. The depth of the wells of the Ramp are continuously variable leading to increased functional bandwidth. Recalling Formula 1 and Formula 2, the depth of the wells determines the low frequency bandwidth limit.

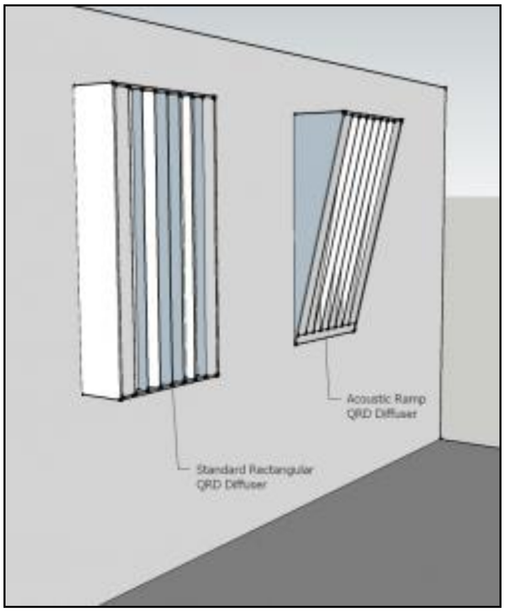


Figure 11 A visual comparison of a standard QRD in the foreground with the Acoustic Ramp in the background

The Ramp's wells vary between a maximum depth of 12 inches to a depth of less than a half inch. The deepest part of the diffuser is usually installed in the corner where the ceiling meets the wall, taking advantage of typically unused space in the room. The diffuser tapers as it descends the wall allowing racks, furniture and other equipment to be placed against the wall without trapping space. The angles formed by the wedge shape of the wells allow the installer to direct reflections away from the sound source. In the most common installation, the wedge shape would direct reflections down toward the floor. In alternative installations, an array of Ramps could be used to direct reflections towards the side walls. In both of these cases, directing sound energy away from the sound sources helps to significantly reduce the effects of comb filtering.

METHODOLOGY

General Methodology Concepts and Techniques

Testing the MDF Prototypes

In the course of the development of the diffuser, several different prototypes were constructed. The most accurate of the hand-made prototypes were built specifically for acoustic testing and they were a set of six 2’ x 4’ diffusers at 1’ deep, based on p=7 quadratic residue sequence: 0 1 4 2 2 4 1 0. The six diffusers were intended to be used in several different configurations, in both vertical and horizontally oriented arrays. This first set of prototype diffusers is shown in Figure 12.

Figure 12 Horizontally oriented array of six p=7 acoustic ramp diffusers.

Each of the six diffusers weigh just under 50 pounds which is at the upper limit of objects that can be moved by a single person. The size of the diffuser combined with the weight makes moving the diffusers somewhat awkward for one person, though possible. The exterior wedge-shaped box is made from 3/4" AB plywood, and the dividers and reflectors are made of 1/4" medium density fiberboard (MDF), the thinnest readily available and inexpensive material. The majority of the internal joints are glue-only, but the box is constructed with glue and 16 gauge air-driven finishing nails. The dividers work better when they are as thin and rigid as possible.[1, p. 296] The reflective material is stretched between two points to form the most rigid surface possible. The reflectors were both glued and tacked down with air-driven brads.

Two facing diffusers may be packed into a single 2' x 4' x 1' box for shipping purposes, though each box weighs in excess of 100 lbs with packing material.

Current Testing Methods for Acoustic Diffusers

Devising a clear, valid, repeatable test of diffusion using reasonable test and measurement resources is far from straightforward [10, pp. 110-155]. The standards for doing so are still under development and represent one leading edge of acoustics research [4].

The most robust diffusion testing would be done in an anechoic chamber with an enormous 1296-microphone array in a perfect hemispherical pattern arranged above a diffuser lying flat on its back. A directional speaker would point straight down at the diffuser and would fire impulses at the diffuser to be received by the test microphones simultaneously. No testing facility with these capabilities is available anywhere, so an alternative testing methodology needed to be devised. In the course of this project, two separate batteries of tests were completed. The first exposed errors in the methodology that were corrected in the second battery of tests.

The testing methods used in the project are based almost entirely on the methodology described in Chapter 4 of Cox and D'Antonio's *Acoustic Absorbers and Diffusers* book[10], which is informed both by their own work and the work of other scholars. The testing method is also described in the "Characterisation and measurement of surface scattering uniformity [AES-4id-2001 (r2007)"][4] which is also largely authored by Cox and D'Antonio.

The test procedure is greatly simplified when a 1D diffuser is tested. A single dimensional diffuser may be tested with an arc of microphones in a hemi-anechoic space, while a two dimensional diffuser requires a hemisphere of microphones in a fully anechoic space. The following image shows early testing using the boundary plane method[11, p. 112], which is suitable for single dimensional diffusers.

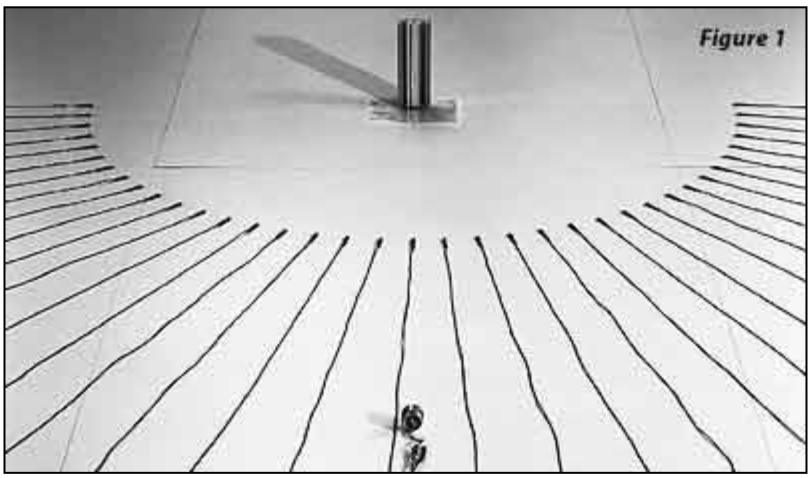


Figure 13 Test configuration from RPG Diffusers Inc with 37 test microphones. [11, p. 112]

There are several difficulties that must be overcome in this testing procedure:

1. The direct sound of the loudspeaker must be eliminated from the test data; the procedure seeks to obtain the reflection off of the diffuser only
2. Reflections off of the walls, ceiling and floor must be eliminated from the test data as well
3. Anomalies of frequency response of both the loudspeaker and the microphone must be normalized

4. Placement of the loudspeaker, diffuser and the microphone must be consistent and correct and within a range of tolerance
5. The loudspeaker must be isolated acoustically from the room in which the test is done
6. Test of the diffuser must be compared to, and informed by, tests of a flat panel of the same size which serves as a control group[1]

After the tests have been conducted, the next problem is the assembly and interpretation of the data. In order to provide a useful picture of the behavior of sound striking a diffusive surface many measurements need to be made, integrated into a larger context of data and then evaluated. A separate measurement needs to be taken for every possible angle of reflection. It would be common to measure every 5 degrees in a semi-circle around the device, requiring the integration of 37 impulse response tests. These 37 test recordings would still only provide information about horizontal diffusion, and are therefore only valid for a 1D diffuser, which has no diffusion performance variability changes vertically and diagonally. Usually the data is interpreted only in the amplitude and frequency domains, though this may change over time.[12] A grid of data is assembled matching an SPL measurement with third-octave frequencies. Each 5 degree measurement yields a list of SPL levels for each frequency band.

[1] The concept of the flat panel control group came under scrutiny during the project and in fact may be more of a hindrance than a help.

Table 1 Example data for third-octave SPL measurements for directivity testing. This is a partial sample showing data from 100-400Hz and from -90 degrees to -40 degrees.

deg/freq	**100**	**125**	**160**	**200**	**250**	**315**	**400**
-90	-32.39	-27.75	-26.22	-25.4	-18.57	-15.45	-13.56
-85	-31.47	-27.14	-24.68	-23.03	-16.78	-14.15	-13.65
-80	-30.1	-25.08	-22.59	-22.38	-18.04	-17.37	-19.3
-75	-28.88	-25.29	-23.96	-24.22	-21.44	-26.67	-21.5
-70	-28.23	-25.54	-25.51	-27.35	-25.47	-22.2	-15.32
-65	-28.1	-24.31	-24.29	-30.15	-29.28	-16.32	-12.32
-60	-28.73	-25.61	-27.31	-31.77	-24.03	-14.73	-12.7
-55	-29.93	-29.61	-33.15	-33.57	-20.35	-14.29	-14.19
-50	-31.17	-30.8	-33.95	-33.38	-20.02	-14.06	-15.27
-45	-32.42	-29.56	-31.23	-31.79	-20.54	-13.96	-15.83
-40	-33.71	-35.13	-35.01	-30.11	-20.19	-15.13	-18.97

Table 1

The testing of the diffuser and a like-sized flat panel is the first step of the process. Next the data must be extracted and organized into grid like that shown above. Finding a way of reducing the complexity of the data into an easy to understand format is quite difficult however. There has been a lot of controversy in the acoustics community over what method of describing diffusion is the most useful. Creating good mathematical models for diffusion would permit software companies to model diffusers effectively and would allow architectural acoustic design to take place in the virtual world. Finding a good metric for evaluating diffusers would also permit the comparison of different styles and models of diffusers in a scientific and objective manner. Currently, there are two commonly-accepted metrics that are in use for describing and comparing diffusion: the Diffusion Coefficient and the Scattering Coefficient.[10]

Neither of these coefficients proved to be fully adequate to describe the behavior of the diffusers under test situations because of their inherent simplification of the diffusive behavior. They were however, excellent starting points for an in-depth investigation into the performance of the Acoustic Ramp. Both the Diffusion and Scattering Coefficients are derived from using the actual data, so the least controversial and most accurate way of evaluating the performance of a diffuser is with the actual raw directivity data. The reduction of diffusive behavior into a single-curve measurement over-simplifies the understanding of the complexity of diffusive behavior. Diffusion involves a large number of variables and alters four essential features of a signal: time, frequency, amplitude and direction of propagation. A two-axis graph of frequency and Diffusion or Scattering Coefficient is a temping simplifying option, but lacks important details like the nature of the polar distribution. It is recommended that the third-octave data in a visual form (see Visualizing Data from Diffusion Testing) be used to evaluate the performance of the diffuser.

Defining Diffusion

Specular Reflections and Edge Diffraction

In order to properly understand diffusion, one must first understand reflection, and more specifically specular reflection. A reflection occurs whenever acoustic energy strikes a hard surface. A specular reflection is the type of reflection made when sound strikes a large flat hard surface and bounces creating a narrow directivity pattern. A scattering reflection is the reflection spreads over a wide angle of directivity.

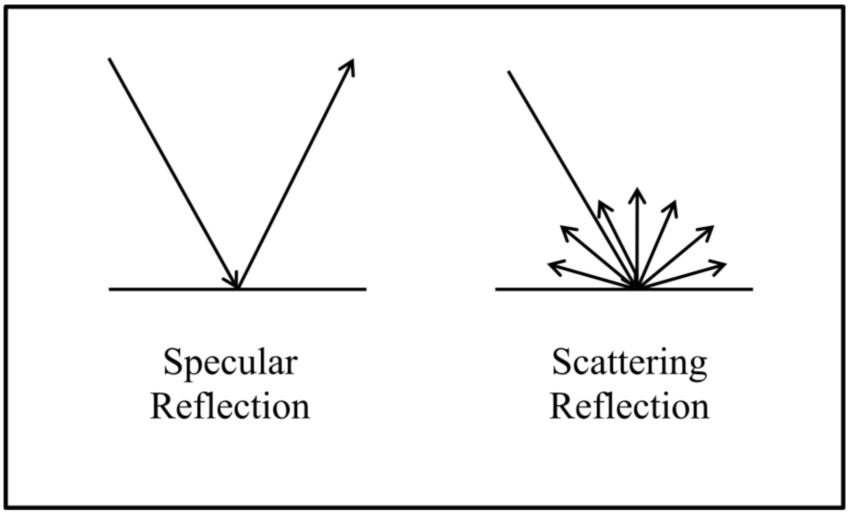


Figure 14 Specular Reflection vs. Scattering of Energy

Frequencies that are smaller than the reflective panel will reflect so that the angle of reflection is equal to the angle of incidence (see Figure 14) but in the opposing direction. For instance, a sound coming from 45 degrees to the left of a panel would reflect to 45 degrees to the right. The area where a specular reflection goes is referred to as the specular zone[13] and is used generally to refer to the behavior of higher frequencies. The larger, more rigid and more massive the panel becomes, the more directional the spectral reflection becomes in higher frequencies. In the case of smaller reflective panels, diffraction causes the edges of the panel to act as a sort of diffuser for a specific group of frequencies. The edges act as a new sound source. This specific behavior is known as the edge effect or as edge diffraction[10, p. 120]. The reflections become less specular and more diffuse as frequencies decrease. Frequencies below 400

Hz are often compared to waves similar to waves in liquid in a wave tank, while higher frequencies are often thought of as rays, more akin to light.[1, p. 236]

In the following graph (Figure 15), the amount of diffusion of a flat panel is plotted using the diffusion coefficient, which will be explained and described later in The AES Autocorrelation Diffusion Coefficient section.

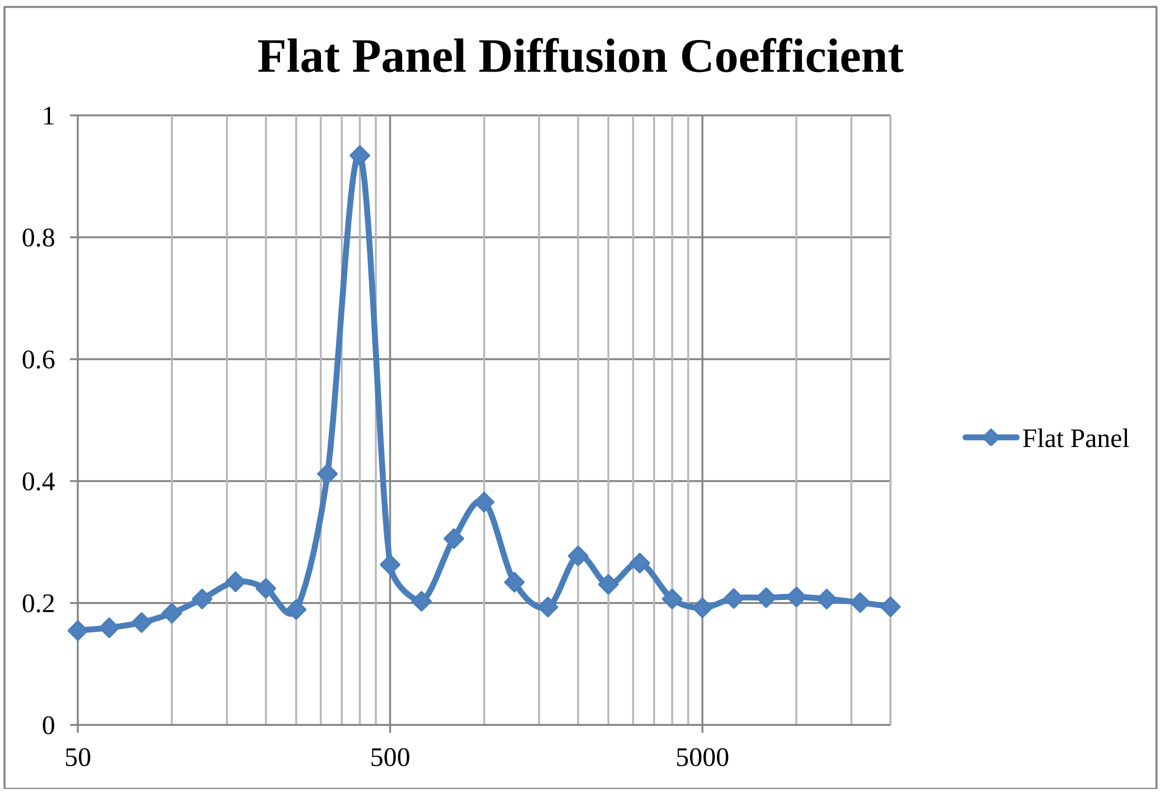


Figure 15 The diffusion coefficient of a flat panel shows diffusive behavior at 400 Hz and at 1kHz.

It is tempting to assume that the size of the panel (2' x 4') would correlate to the diffused frequencies wavelengths. If so, interesting results could be expected around 282.5 Hz and 565 Hz based on wavelength calculations based on the size of the panel. It is possible that surface area, materials, edge tolerance and shape, distance between the source and the reflector all have an effect on which frequencies become scattered through diffraction. [13] [14] [15]

The distance between the source and the receiver and the flat panel is critical to the width of specular reflection. Assuming a single point sound source is being used, a five foot test radius has an expected reflection of 22.1° from a flat panel (see Figure 16). This is due to the phenomenon that reflected sound seems to come from a phantom source the same distance from the reflector but from past the reflector (often appearing as if it is inside the wall!).[1, pp. 235-237] This phenomenon is shown very clearly by the sonogram depicting the flat panel directivity data in Figure 17. Sonograms are explained in the Sonogram Results section later in this paper.

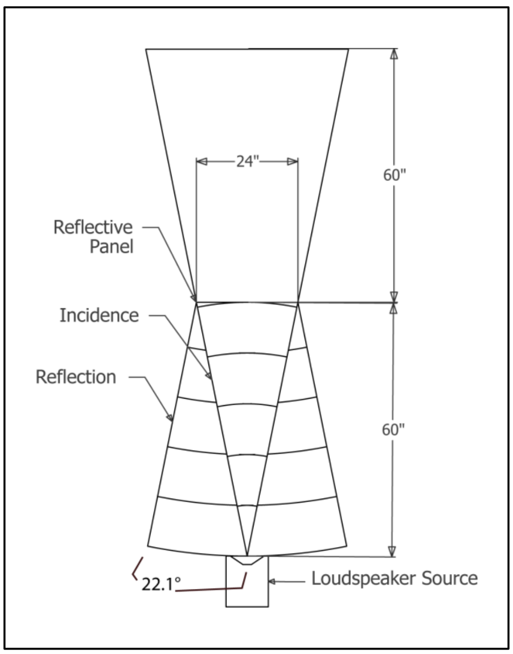


Figure 16 Angle from reflection from a flat surface at 5 feet (60 inches) is 22.1 degrees. [13]

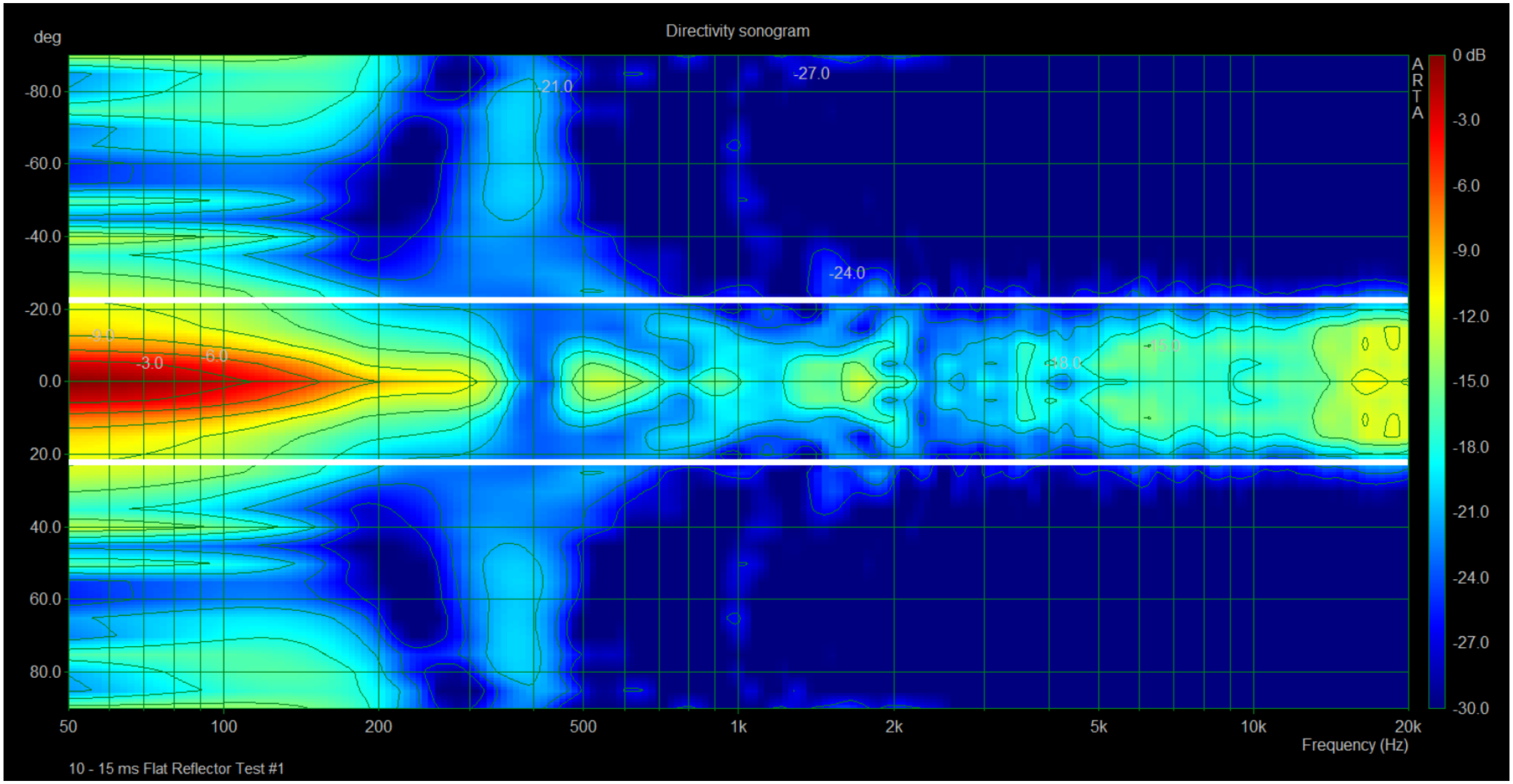


Figure 17 Flat Panel sonogram with the 22.1 degree point highlighted to show relationship to the width of the spectral content of the reflection.

Diffusion

When a sound strikes a diffusive surface however, the reflected sound is attenuated in the specular zone because the energy is being distributed across many different directions.. The more specular the reflected energy from a flat surface is, the more intense it is in the specular zone. If the energy is spread and distributed over a larger surface area, the energy is attenuated at any one receiver location.

A perfect diffuser would scatter reflections of all frequencies in an omnidirectional pattern.

Frequency

Neither reflection nor diffusion are ever flat in frequency response however. Every material has its own properties of absorption. Thinner material often behaves like a membrane and absorbs resonant frequencies, while thicker and rougher materials might reflect low and mid range frequencies but absorb and diffuse upper frequencies. Shape and size of diffusers affect the frequencies that are reflected as well.

As mentioned earlier, Schroeder determined that his quadratic residue diffusers had a frequency response that was defined by the depth and width of the wells. The low frequency boundary was defined by the frequency with the wave length four times the depth of the deepest well and the high frequency was bounded by the frequency two times the width of the wells. Thus a diffuser with the following properties

Well Maximum Depth = 1 foot

$$\lambda = \frac{1130\ ft/sec}{4(Max.Depth)}$$

Well Widths = 1/10th of a foot

$$\lambda = \frac{1130\ ft/sec}{2(Width)}$$

would yield an effective bandwidth of:

282.5 Hz to 5650 Hz

<u>Time and Phase</u>

Diffusers also create time and phase changes in reflected sound. This is primarily a function of there being different distances from the sound source created by the variable depths of the wells. The more variation there is in well depth, the more time and phase changes there are. In the prime=7 standard QRD's, there are zero depths, 1 unit depths, 2 unit depths and 4 unit depths, which divide the time of arrival into 4 separate times of reflection.

Visualizing Data from Diffusion Testing

There are a variety of different tools for viewing the raw data captured from diffusion testing: polar patterns, sonograms, and waterfall charts. Further, the data can be simplified using the Diffusion Coefficient formula to create an easy-to-read scatter chart.

Polar Pattern Charts

Scattering is often measured with a directivity polar pattern graph to show how energy is distributed at a specific frequency. One advantage of the polar pattern graph is that the graph is very similar to the human understanding of direction and scattering. Many people are already familiar with polar patterns because they are the dominant graphic used to describe microphone pickup patterns. The biggest problem with using polar patterns is that they are not good for showing more than one frequency band at a time. A couple of curves may be overlaid on each other, but they tend to obscure the information of the other frequencies that are involved.

The polar pattern below is taken from the second round of acoustic testing of the horizontal configuration of the diffusers. It shows only the 1/3 octave band of 1250 Hz, but does show the behavior very clearly and in a manner that is easy to visualize and understand. Amplitude is shown as a function of distance from the center of the polar plot with louder signals being further away from the center. The directionality of reflected energy matches that of the real world. -45° corresponds to -45° looking down onto the reflective object at the center with the source in front of the reflector.

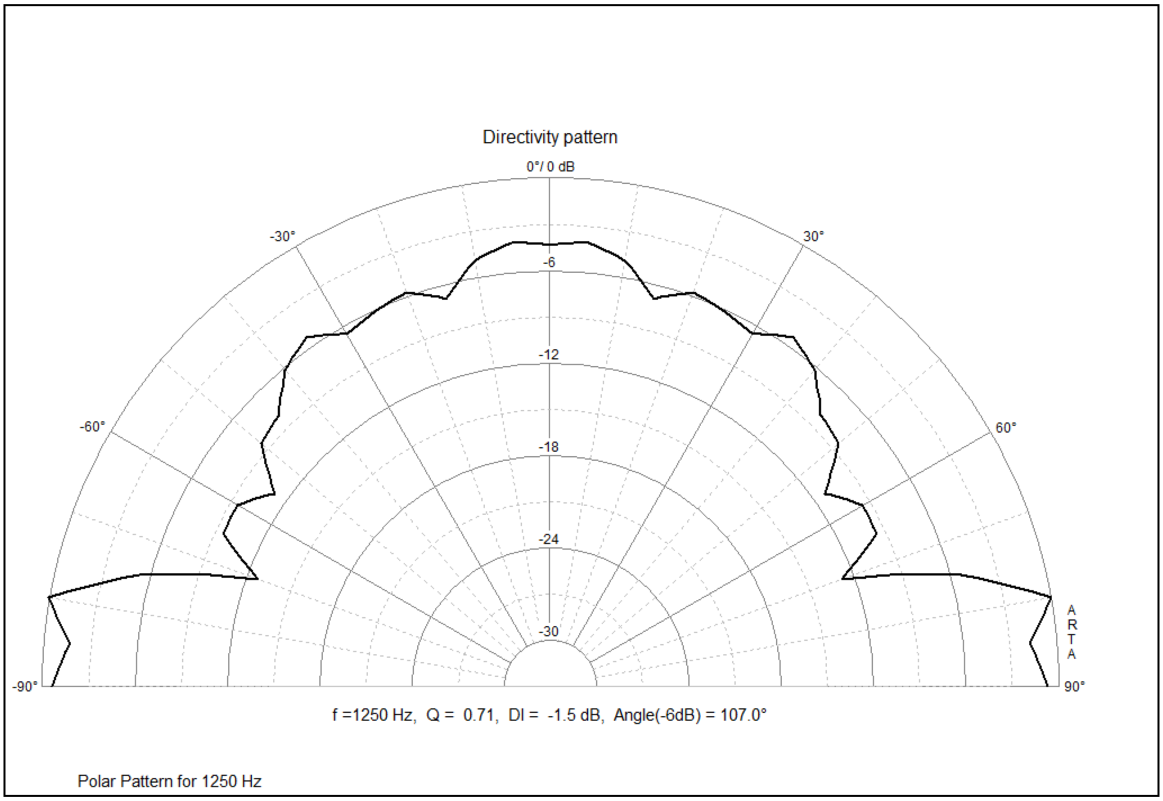


Figure 18 Polar Pattern showing directivity of 1250 Hz.

Sonogram Chart

Another visualization tool for directivity is the sonogram chart, which may be slightly more difficult to read, but does show directivity behavior for all frequencies and angles clearly at the same time.

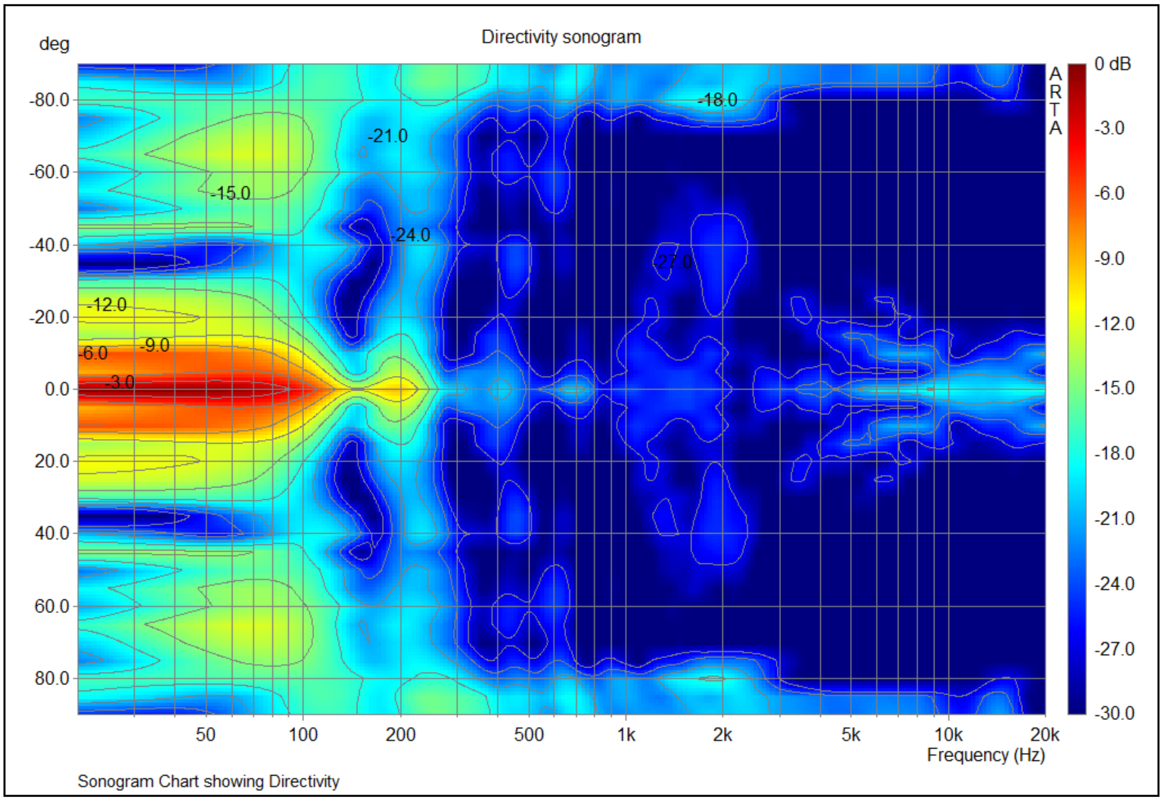


Figure 19 Sonogram Chart

Frequency is represented on the X-axis. The Y-axis represents the angle of reflection and the color temperature indicates amplitude. Vertical bands of similar coloring at 200 Hz, 400 Hz, 500 Hz and 600 Hz means that there is a relatively even distribution of energy in those frequency bands. Hot spots, as shown in the low frequencies up to 200 Hz and in areas above 5kHz show an uneven distribution of energy scattering that approaches the behavior of specular reflection.

Waterfall Charts

Waterfall Charts are another tool that can be used to view directivity data. Amplitude is represented on the Y-Axis, direction is indicated on the X-axis and frequency is represented on the Z-axis. In the case of the examples below, amplitude is also shown using color temperature. The 3D effect of the chart that helps the viewer visualize and understand the data can also obscure parts of the data unfortunately. Details that fall behind a tall area of the chart are hidden. Waterfall charts can be manipulated so that different parts of the data are represented with the various axes. The following two waterfall charts depict the same data, but with two different orientations.

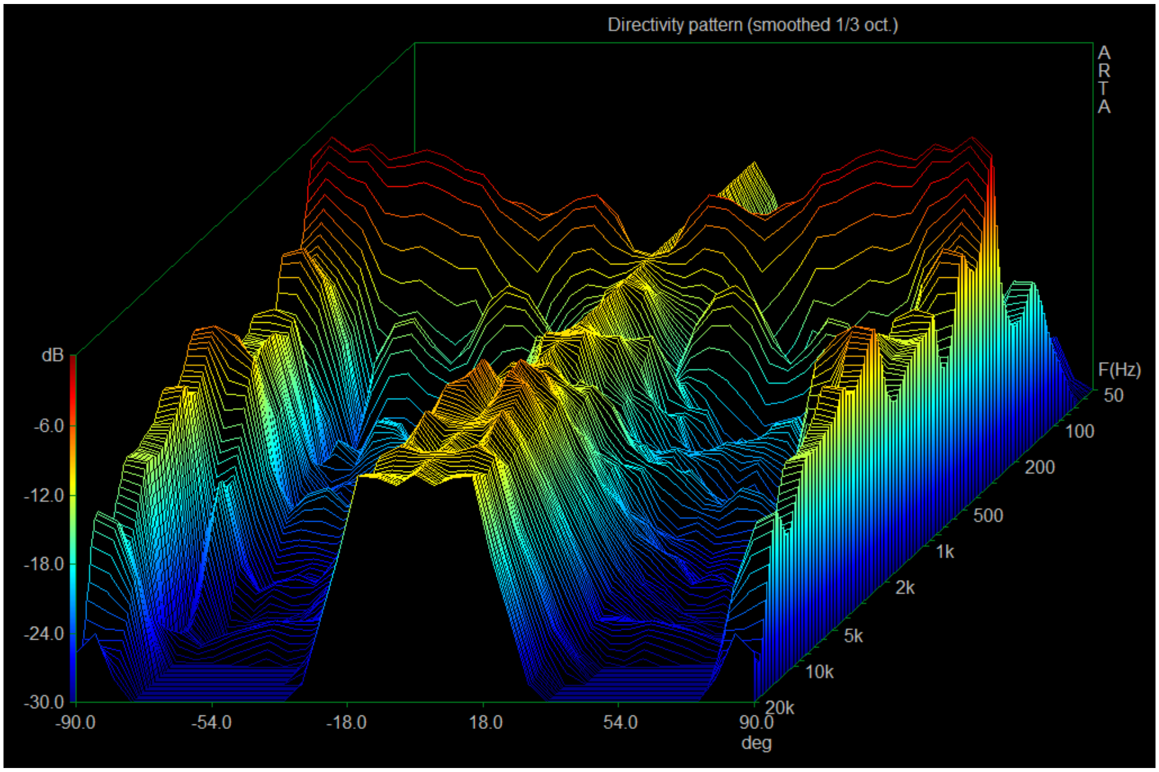


Figure 20 3D Waterfall Chart angle in the X-axis

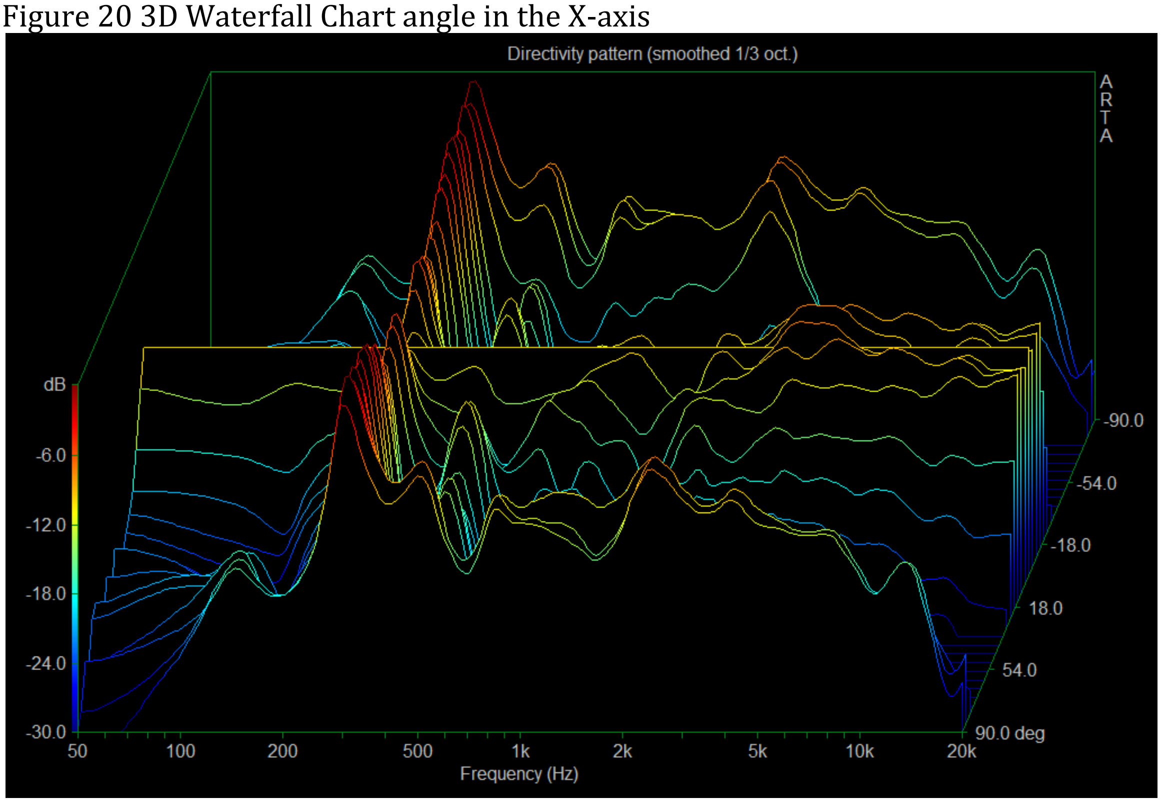


Figure 21 3D Waterfall chart with Frequency in the X-Axis

Of all of the visualization tools, the sonogram is the best combination of reading simplicity and complexity of data represented. The user can view and analyze the complete directivity response for all frequencies, degrees of reflection and amplitudes at the same time.

Coefficients: Methods for Simplifying and Interpreting Data

Coefficients are reductions of the directivity data from the testing into a single value per single frequency band curve. They are useful for general discussions of the performance or quality of diffusers, but their very nature obscures details of the scattering behavior.

The ISO Scattering Coefficient

In its most basic form, the ISO Scattering Coefficient (s_{ψ})is a comparison of the reflected specular energy, reflected non-specular energy and the total reflected energy. As the name implies, this Coefficient has already been approved by the International Standards Organization (ISO) and is considered to be somewhat less controversial that the AES Autocorrelation Diffusion Coefficient which is discussed in the next section. The ISO Scattering Coefficient is defined in the following formula:

$$s = \frac{\alpha_{spec} - \alpha_s}{1 - \alpha_s} = 1 - \frac{E_{spec}}{E_{total}} \quad (3)$$

Formula 3 ISO Scattering Coefficient [10]

In English, the formula states that the Scattering Coefficient is equal to the spectral energy reflections minus the scattered energy reflections divided by one minus the scattered energy reflections. The Scattering Coefficient is also equal to one minus the specular energy divided by the total energy.

Though simpler and less controversial than the AES Autocorrelation Diffusion Coefficient (discussed below), the ISO Scattering Coefficient measures the amount of energy that is not in the specular zone. It does not measure how evenly the energy is distributed in the new directions of reflection. It indicates that reflection is not specular, but does not differentiate between a simple change of reflection and the diffusion of energy. This has motivated the search for a better diffusion metric that does describe the quality of diffusion.

The AES Autocorrelation Diffusion Coefficient

The current AES-approved method for quantifying diffusion is the Diffusion Coefficient (d_ψ) based on the autocorrelation formula which has been borrowed from optics and statistics[16].

$$d_\psi = \frac{\left(\sum_{i=1}^{n} 10^{L_i/10}\right)^2 - \sum_{i=1}^{n}\left(10^{L_i/10}\right)^2}{(n-1)\sum_{i=1}^{n}(10^{L_i/10})^2} \qquad (4)$$

Formula 4 The Autocorrelation Diffusion Coefficient Formula.[10]

This is a formula for a single frequency band. In order to obtain the type of plotted responses that Cox/D'Antonio show, one needs to apply this formula to all of the frequency bands of interest. Here are the meanings of the variables:

Table 2 The meanings of the variables in the Diffusion Coefficient Formula.

d_ψ	Diffusion Coefficient of a Single Frequency Band
n	The number of positions of microphones you used in your directivity test. A 5° granularity would yield 37 receiver positions in a semi-circle, for instance
i	A counting variable very much like that used in a FOR/NEXT statement in programming: For $i = 1$ to n; Next i
L_i	The Sound Pressure Level at the position marked by i. The subscript is only a way of denoting that there are many different L's.

Table 2

Essentially, the term L_i is the list of SPL values for each of the receiver positions at a specific frequency. The data that is used in the formula is shown below. Excel 2007 with Data Analysis was used as the spreadsheet application to do the computations.

The following table (Table 3) shows the raw SPL data for a flat panel. This is the type of data that is used to generate the diffusion coefficient.

Table 3 Third Octave Sound Pressure Levels for a Flat Panel from 250 - 5000Hz.

deg/freq	250	315	400	500	630	800	1000	1250	1600	2000	2500	3150	4000	5000
-90	-20.9	-33.69	-27.18	-28.87	-29.03	-25.16	-33.33	-36.46	-47.29	-31.56	-39.42	-43.84	-43.11	-45.61
-85	-23.28	-28.69	-26.68	-32.04	-27.56	-26.41	-29.65	-31.74	-43.45	-34.22	-37.17	-40.45	-40.75	-39.28
-80	-22.72	-24.12	-27.76	-31.6	-28.53	-30.13	-29.31	-30	-39.11	-33.29	-36.54	-41.43	-37.51	-40.05
-75	-24.37	-28.83	-27.98	-33.74	-27.92	-32.42	-32.72	-31.07	-34.52	-32.53	-36.54	-45.98	-38	-42.03
-70	-21.4	-21.27	-26.32	-32.47	-28.99	-31.29	-30.43	-32.65	-34.55	-32.73	-40.94	-39.35	-40	-40.45
-65	-20.47	-19.55	-25.82	-29.46	-28.25	-30.82	-28.27	-34.64	-33.35	-32.23	-44.27	-40.57	-37.53	-40.26
-60	-21.82	-21.25	-25.12	-26.45	-25.81	-30.39	-28.28	-37.35	-33.39	-35.9	-38.89	-36.46	-41.48	-36.97
-55	-19.74	-19.1	-24.91	-24.85	-25.47	-28.78	-27.65	-31.76	-31.27	-39.73	-36.21	-33.66	-36.09	-37.26
-50	-17.33	-17.03	-25.89	-23.24	-26.19	-28.63	-26.35	-28.31	-31.5	-34.28	-36.61	-36.39	-35.49	-34.63
-45	-18.31	-18.36	-26.04	-24.27	-25.48	-30.45	-29.68	-26.5	-35.84	-27.85	-32.92	-33.65	-34.18	-35.2
-40	-16.92	-15.78	-22.46	-25.4	-24.39	-35.52	-29.55	-25.31	-34.48	-24.77	-31.89	-29.08	-30.2	-31.32
-35	-17.98	-17.6	-22.38	-21.88	-24.94	-27.61	-26.58	-26.23	-22.77	-25.52	-30.63	-30.38	-32.58	-31.77
-30	-16.39	-16.47	-22.47	-19.77	-21.63	-25.31	-31.87	-27.91	-21.87	-24.38	-27.2	-30.42	-27.29	-25.86
-25	-14.48	-14.84	-22.71	-18.88	-19.01	-28.54	-23.35	-30.19	-24.02	-23.95	-28.03	-25.04	-27.19	-25.62
-20	-13.69	-13.95	-22.19	-20.23	-18.9	-21.37	-24.75	-26.33	-19.69	-20.39	-23.76	-23.41	-22.16	-21.19
-15	-13.16	-13.21	-19.68	-22.31	-21.48	-17.68	-19.18	-22.65	-20.87	-17.24	-20.22	-19.73	-19.44	-17.72
-10	-12.13	-11.89	-17.1	-22	-24.96	-18.79	-16.3	-20.72	-18.11	-16.02	-20.35	-17.69	-16.87	-16.11
-5	-9.46	-9.18	-14.72	-17.66	-20.04	-16.77	-16.19	-18.54	-11.95	-19.12	-19.06	-18.26	-15.3	-13.57
0	-7.42	-7.47	-11.97	-14.84	-16.58	-12.41	-14.14	-19.34	-10.74	-14.08	-23.05	-17.09	-19.6	-17.11
5	-9.46	-9.18	-14.72	-17.66	-20.04	-16.77	-16.19	-18.54	-11.95	-19.12	-19.06	-18.26	-15.3	-13.57

10	-12.13	-11.89	-17.1	-22	-24.96	-18.79	-16.3	-20.72	-18.11	-16.02	-20.35	-17.69	-16.87	-16.11
15	-13.16	-13.21	-19.68	-22.31	-21.48	-17.68	-19.18	-22.65	-20.87	-17.24	-20.22	-19.73	-19.44	-17.72
20	-13.69	-13.95	-22.19	-20.23	-18.9	-21.37	-24.75	-26.33	-19.69	-20.39	-23.76	-23.41	-22.16	-21.19
25	-14.48	-14.84	-22.71	-18.88	-19.01	-28.54	-23.35	-30.19	-24.02	-23.95	-28.03	-25.04	-27.19	-25.62
30	-16.39	-16.47	-22.47	-19.77	-21.63	-25.31	-31.87	-27.91	-21.87	-24.38	-27.2	-30.42	-27.29	-25.86
35	-17.98	-17.6	-22.38	-21.88	-24.94	-27.61	-26.58	-26.23	-22.77	-25.52	-30.63	-30.38	-32.58	-31.77
40	-16.92	-15.78	-22.46	-25.4	-24.39	-35.52	-29.55	-25.31	-34.48	-24.77	-31.89	-29.08	-30.2	-31.32
45	-18.31	-18.36	-26.04	-24.27	-25.48	-30.45	-29.68	-26.5	-35.84	-27.85	-32.92	-33.65	-34.18	-35.2
50	-17.33	-17.03	-25.89	-23.24	-26.19	-28.63	-26.35	-28.31	-31.5	-34.28	-36.61	-36.39	-35.49	-34.63
55	-19.74	-19.1	-24.91	-24.85	-25.47	-28.78	-27.65	-31.76	-31.27	-39.73	-36.21	-33.66	-36.09	-37.26
60	-21.82	-21.25	-25.12	-26.45	-25.81	-30.39	-28.28	-37.35	-33.39	-35.9	-38.89	-36.46	-41.48	-36.97
65	-20.47	-19.55	-25.82	-29.46	-28.25	-30.82	-28.27	-34.64	-33.35	-32.23	-44.27	-40.57	-37.53	-40.26
70	-21.4	-21.27	-26.32	-32.47	-28.99	-31.29	-30.43	-32.65	-34.55	-32.73	-40.94	-39.35	-40	-40.45
75	-24.37	-28.83	-27.98	-33.74	-27.92	-32.42	-32.72	-31.07	-34.52	-32.53	-36.54	-45.98	-38	-42.03
80	-22.72	-24.12	-27.76	-31.6	-28.53	-30.13	-29.31	-30	-39.11	-33.29	-36.54	-41.43	-37.51	-40.05
85	-23.28	-28.69	-26.68	-32.04	-27.56	-26.41	-29.65	-31.74	-43.45	-34.22	-37.17	-40.45	-40.75	-39.28
90	-20.9	-33.69	-27.18	-28.87	-29.03	-25.16	-33.33	-36.46	-47.29	-31.56	-39.42	-43.84	-43.11	-45.61

A set of Excel spreadsheet formulas was devised to compute the coefficient. These formulas are shown below.

$$\left(\sum_{i=1}^{n} 10^{L_i/10}\right)^2 \quad \text{=POWER(SUM(POWER(10,(B2:B38/10))),2)} \tag{6}$$

$$\sum_{i=1}^{n} \left(10^{L_i/10}\right)^2 \quad \text{=SUM(POWER(POWER(10,(B2:B38/10)),2))} \tag{7}$$

Formula 5 Excel Spreadsheet formula for the first term
Formula 6 Excel Spreadsheet formula for the second term

The Normalized Diffusion Coefficient[10]

In an effort to be able to compare one diffuser to another that were not tested together, the Normalized Diffusion Coefficient was devised. A like-sized flat panel is tested at the same time that the diffuser is tested and is used as a control. The response of the flat panel is subtracted from the response of the diffuser, so that the new coefficient reflects only the effect of the diffuser and not the flat panel. The reason that normalization is required is that flat panels do not yield only specular reflections, but in fact display diffusive qualities at certain frequencies based on diffraction at the edges of the panel. This diffraction is known as the edge effect. D'Antonio and Cox show[10] that this diffraction effect increases in the lower frequencies. In an effort to remove this flat panel anomaly, the diffusion coefficient of the flat panel ($d_{\psi,r}$) is subtracted from the diffusion coefficient of the diffuser under test (d_{ψ})as shown in Formula 7 The Normalized Diffusion Coefficient below. This yields the normalized diffusion coefficient ($d_{\psi,n}$).

$$d_{\psi,n} = \frac{d_{\psi} - d_{\psi,r}}{1 - d_{\psi,r}} \qquad (8)$$

Formula 7 The Normalized Diffusion Coefficient

The problem with this idea, as will be shown in the DISCUSSIONS section, is that the edge effect varies based on the size of the flat panel, the distance between the source and the panel, and other factors such as the tolerance of the edge itself and the thickness of the panel. There is no reason to believe that the edge effect of flat panel will be similar to a diffuser of the same size. These factors cast doubt on the accuracy and validity of the normalized diffusion coefficient as a means of comparing diffusers from different tests or different facilities.

Specifications of Test Equipment

The testing equipment used during the two test sessions is more than adequate for the task, but certainly not the state of the art. The basic equipment configuration is relatively simple. A loudspeaker amplifies a test signal and directs acoustic energy as the object under test. A test microphone is used to capture the energy reflecting off of the object and the signal from the microphone is converted into digital signals that are then analyzed with specialized software. The loudspeaker, microphone, microphone preamp and audio interface all need to be of sufficient quality to have relatively flat frequency responses and fast enough to be able to document the time domain accurately. The acoustic testing software must be able to compare the output of the test signal to the input of the microphone signal to generate a meaningful data analyses.

<u>Specifications of Critical Equipment</u>

Earthworks TC-25 Microphone

Frequency Response: 9Hz to 25kHz ±1/-3dB

Polar Pattern: Omnidirectional

Sensitivity: 8mV/Pa (-42dBV/Pa)

Maximum Acoustic Input: 145dB SPL

Noise: 27dB SPL equivalent (A weighted)

The TC-25 microphone was selected because of its extremely flat frequency response and the speed with which it reacts to air pressure. The TC stands for Time Coherent. Omnidirectional microphones have the tendency to possess a flatter frequency response because there is no proximity effect and the diaphragm of the microphone is exposed to the air only on one side.

Mackie HR824 Powered Loudspeaker

Free Field Frequency Response: 39Hz to 20kHz ±1.5 dB

THD: <0.035%

SNR: >102 dB

Residual Noise at Maximum Gain: <8dB SPL @ 1 Meter

The Mackie powered monitors are relatively flat, inexpensive loudspeakers that are small enough to be moved easily. The speaker is bi-amped and extremely efficient and so is able to produce SPLs in excess of 100dB without difficulty.

Daking Audio Mic Pre One

The Daking Audio Mic Pre One is a fast solid-state preamp with plenty of headroom to permit accurate reproduction of transients in the time domain. Very little gain is required because of the high sound pressure levels and the sensitivity of the TC-25 microphone, but the preamp has plenty to spare. Due to the speed of the preamp, gain levels need to be kept quite low to avoid clipping because the preamp is able to track transients accurately.

MOTU Traveler

The Traveler is a 8in-8out 24 bit 192kHz AD/DA and audio interface with a flat frequency response in the audible range. It has 4 on-board preamps that are of serviceable quality, but lack the speed of the Daking Audio preamp. The drivers for the Traveler are stable on Windows XP SP3 and offer options in ASIO and WDM.

ARTA Acoustic Testing Software[17]

ARTA is a full-featured impulse response and analysis software package that includes tools for directivity analysis. The software is able to import and export many different kinds of data including third-octave SPL measurements and raw sample audio data as well. The software generates several different types of test signals including the swept sine wave that I used in my testing. The application then deconvolves the recorded response into the actual impulse response. ARTA is capable of both single channel (non-normalized) and dual channel loop-back testing which normalizes timing to when the impulse is sent from the audio interface. The directivity tool in ARTA takes the impulse response from many specially named files and creates polar responses, sonograms, and waterfall charts. Further, ARTA will allow the user to export the directivity data as .CSV or Comma Separated Values files that can be subsequently evaluated in tools like Excel or Matlab.

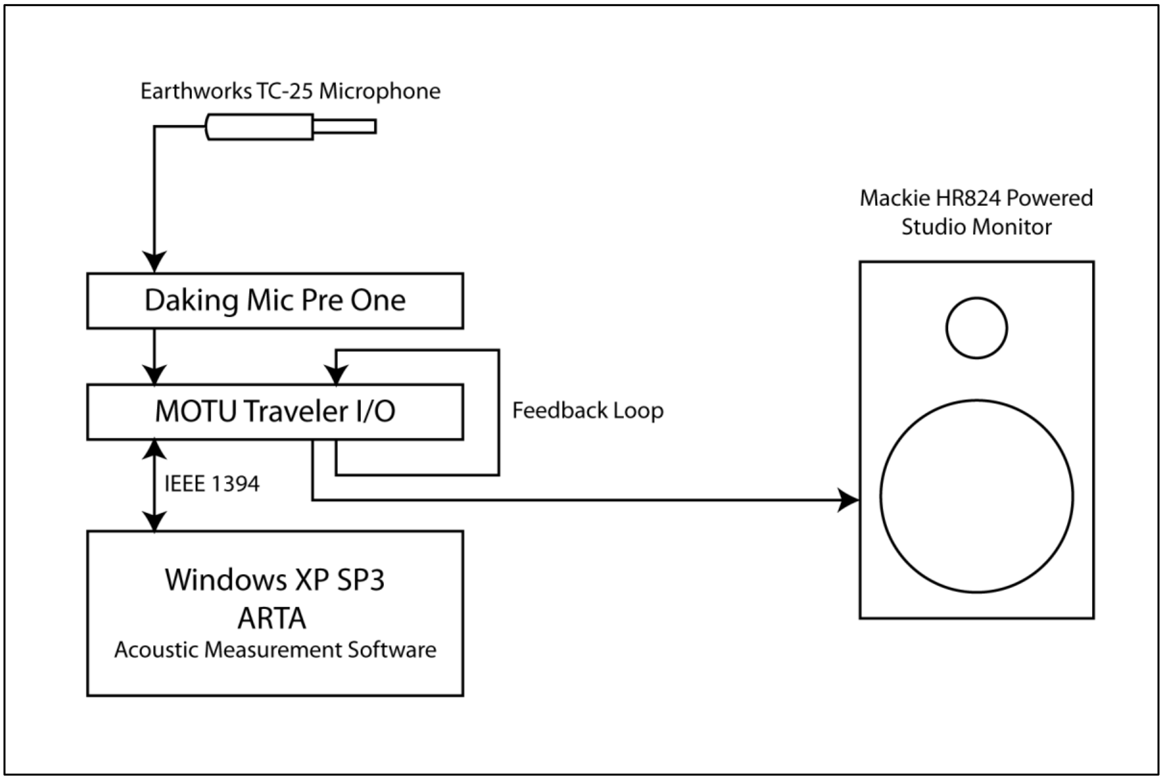


Figure 22 Signal flow diagram for acoustic testing in two-channel mode. The second channel is a feedback channel for time aligning the impulse response to the captured acoustic audio data.

Acoustic Ramp Test Session 1

The first test session took place May 14, 2011 in the Concert Hall at the University of Massachusetts Lowell's Durgin Hall. The stage of this performance space is large enough to allow for an approximately 44 ms reflection-free time window with which to extract test results.

Procedure

The testing procedure implemented a version of the boundary plane test method[10] using a 20 foot radius and a quarter circle arc (see Figure 24). A quarter circle arc was deemed sufficient because the testing was of a symmetrical object, a 6-unit array of Acoustic Ramps. The test radius employed a 5 degree resolution, the most acceptable balance between difficulty and accuracy and the accepted AES standard. [4] Each angle required a separate impulse response measurement, though two were taken to eliminate intermittent noise problems. A Mackie HR824 powered monitor amplified the test signal and the ARTA software package used a swept sine wave to create impulse response measurements.

The Acoustic Ramp is not a simple one-dimensional diffuser, so strictly speaking, a single boundary plane test is not a complete measure of the diffusive behavior. A hemispherical test was probably not appropriate either because the angles of the reflective faces of the wells were expected to be directional instead of omnidirectional like a true 2-D diffuser. A hemispherical test is also nearly impossible to do without special equipment and a specialized acoustic testing space. Two separate boundary plane tests with the diffusers in first horizontal and then vertical positioning would be sufficient to measure the bulk of the scattering characteristics of the diffuser.

The expectation was to find a relatively even diffusive property in the vertical orientation of the diffuser with the calculated frequency range and hot spots in the horizontal orientation corresponding to the angles of reflection of the rears of the wells.

The following figure show the various angles of incidence and reflection and where it was expected to see increases in sound pressure.

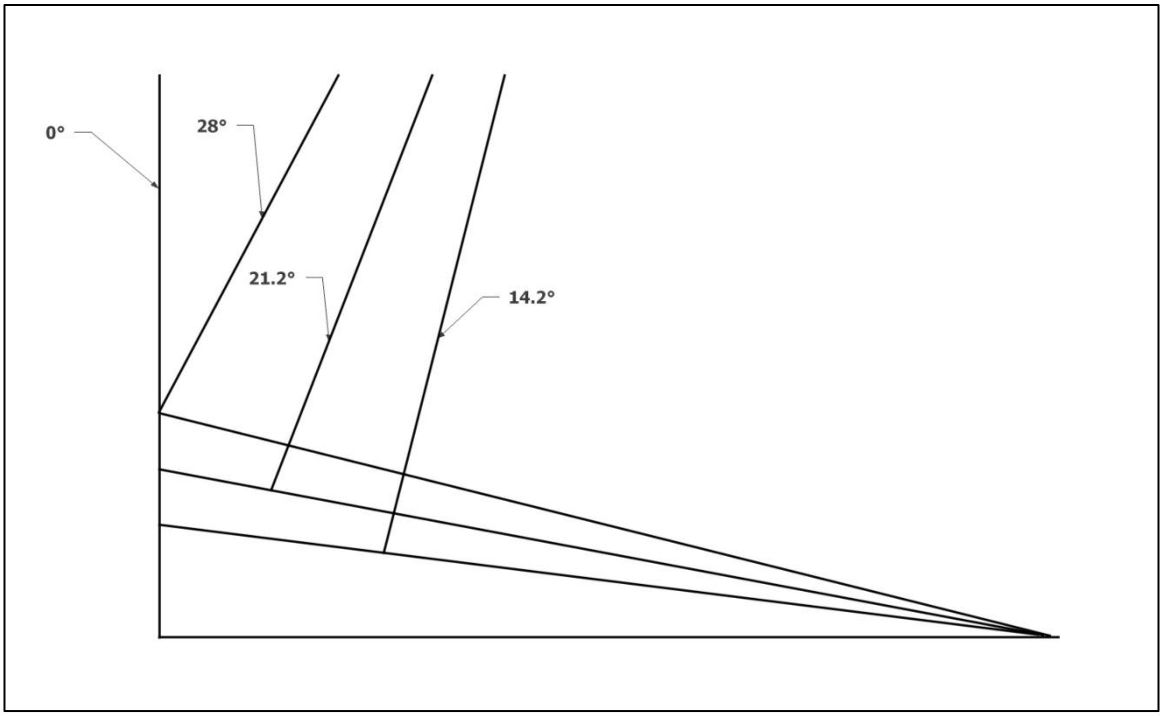


Figure 23 Angles of incidence and reflection on the Acoustic Ramp

It was expected that there would be increased SPL at 30° (~28°), 20° (~21.2°), 15° (~14.2°) and 0° because of the angles of reflection shown above.

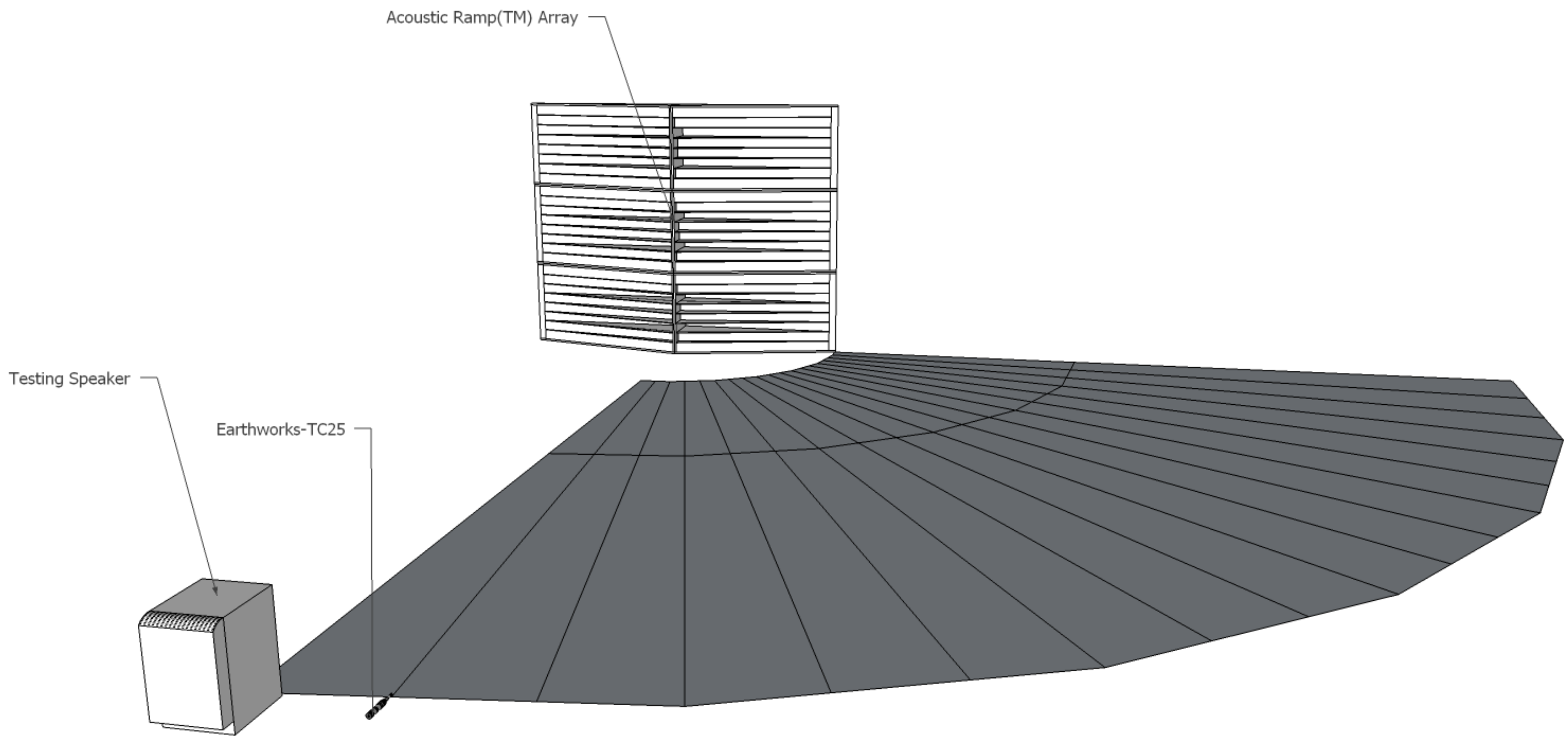


Figure 24 The intended test setup for the 6-diffuser horizontal array in Test Session 1. This configuration uses 1 loudspeaker, 1 test microphone and a 20 foot radius.

Documented Procedure

Figure 25 University of Massachusetts Lowell's Concert Hall stage with the shell installed. This is the largest available space for acoustic testing in the Music Department's Durgin Hall. From center down stage nearly 25 feet of testing distance is available before the first reflection point.

The Concert Hall at the University of Massachusetts Lowell campus in Durgin Hall is the largest space in the Music Department and allows for time-windowed acoustic testing within 44 ms before reflections interfere with the gating process. During the testing procedure the performance shell was in place. The performance shell is a mobile reflective wall designed to project sounds on the stage out into the audience. The shell pieces are poly-cylindrical in shape to obtain diffusive qualities. The first portion of the testing procedure is to scribe the testing radius onto the floor of the stage so that the locations of the diffusers, loudspeaker and microphone are precise and fixed. This procedure is the longest part of the testing process. First the stage is bisected from to back (see Figure 26). The center point, where the middle of the diffusers will be placed (see Figure 28), is fixed along this dividing line approximately 10 feet from the upstage shell to create a significant time delay between the arrival of reflections from the diffuser and the reflections from the shell. The loudspeaker will also be placed on this center line, 25 feet downstage from the center point (see Figure 30). The quarter-circle is drawn using a 25 foot string and marking chalk and the 5° marks are located using trigonometry based on the angle and the length of the two legs of the triangle. A white piece of tape is placed at each of the test points along the circumference of the circle and the exact test point is marked with cross hairs with a Sharpie (see Figure 30). The testing procedure is repeated with the diffusers in three configurations: a horizontal array of 6 diffusers (see Figure 32), a vertical array of 3 diffusers (see Figure 34) and a reversed horizontal array as a flat panel of 6 diffusers (see Figure 33).

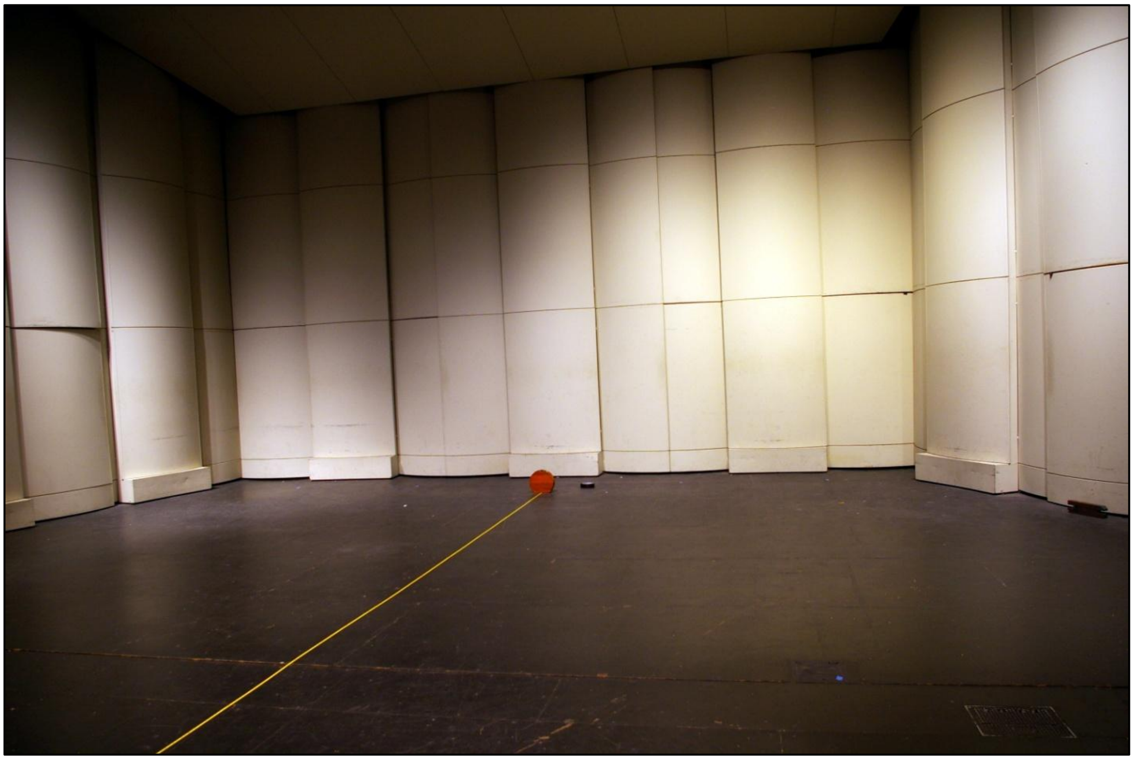


Figure 26 The stage is bisected with a landscaping tape and held in place with an Earthworks microphone case. This is the initial measurement from which the testing radius is created.

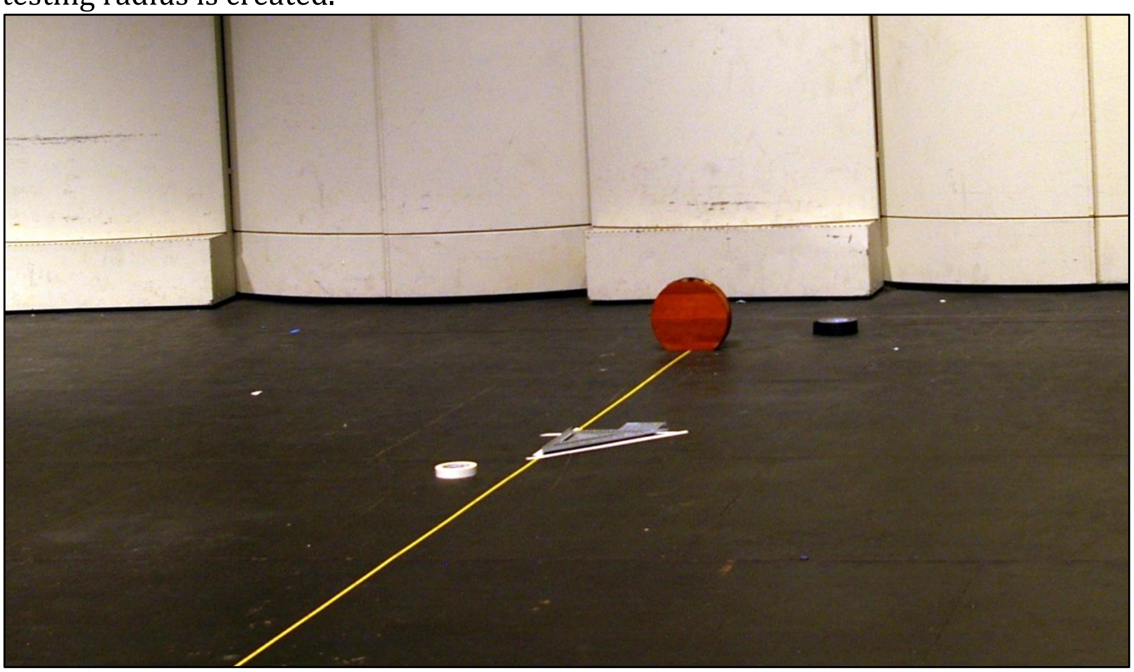


Figure 27 Using a carpenter's square at 25 feet from the speaker location. It was determined that the 25 foot mark was in fact too close to the orchestra shell and would likely produce confusing reflections.

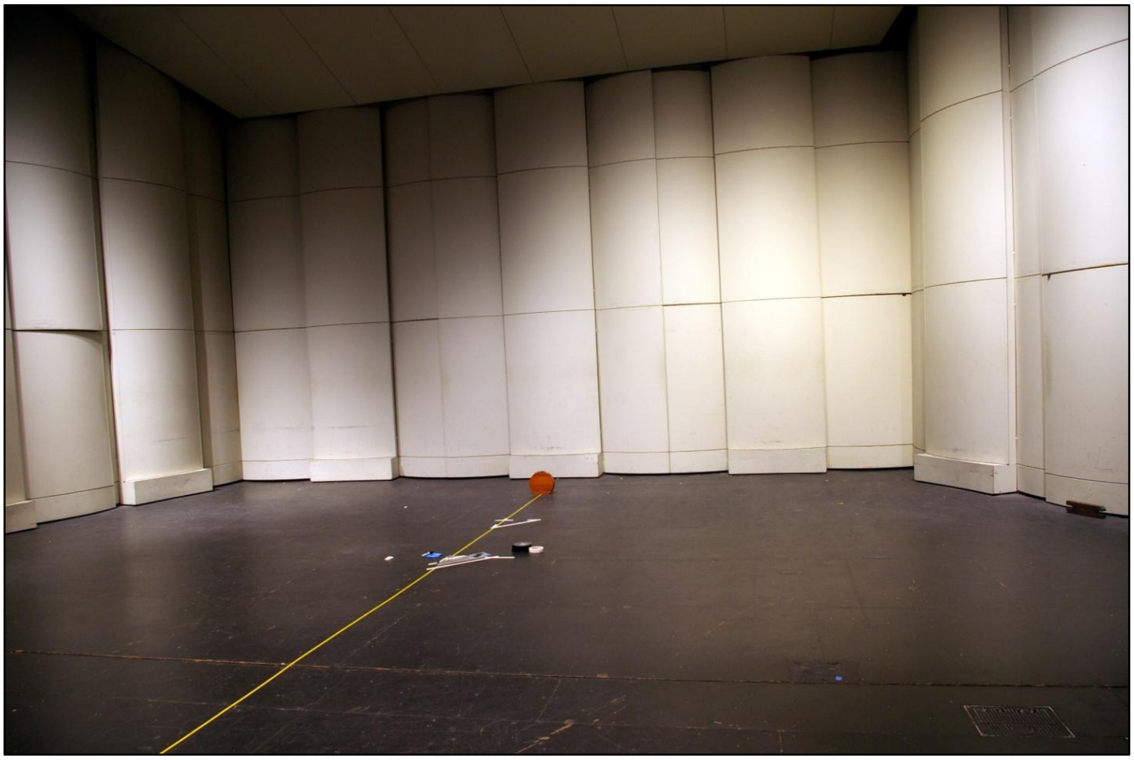


Figure 28 Defining the vertex of the center of the test radius using the carpenter's square at the 20 foot mark. This becomes the center of the diffuser array.

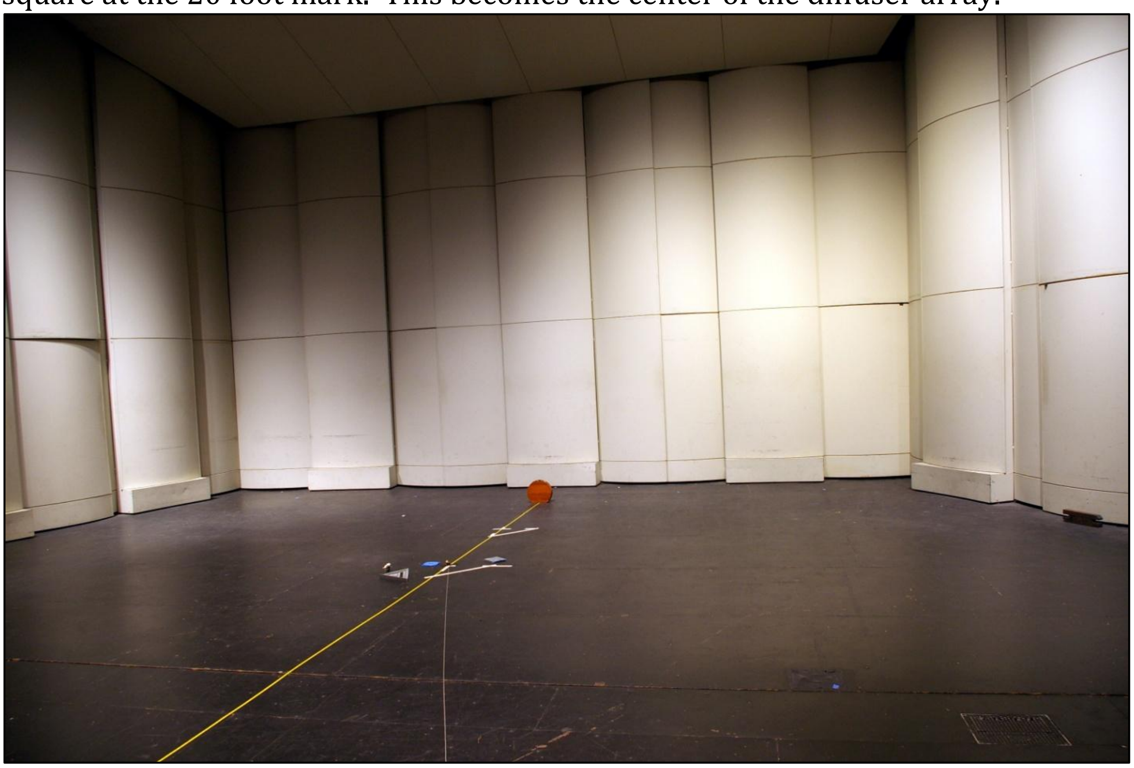


Figure 29 Using a string to measure the circumference of the test circle.

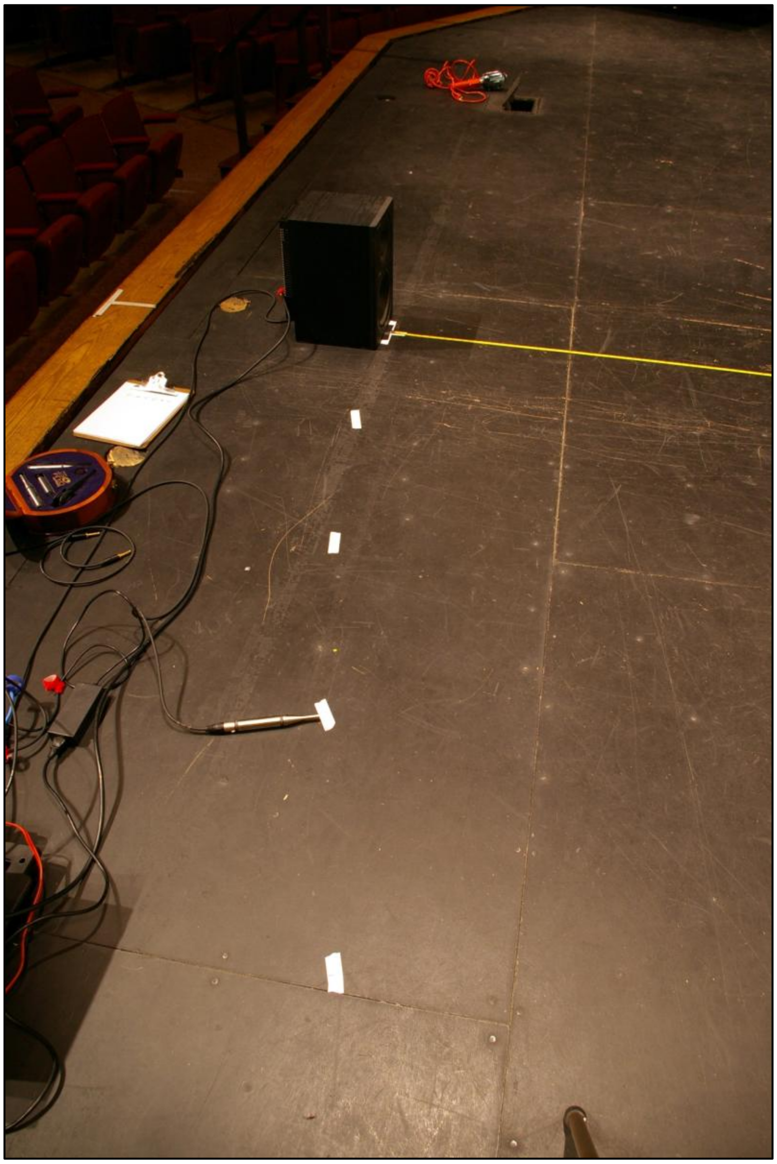


Figure 30 The testing speaker, a Mackie HR824 studio monitor, and the Earthworks TC25 testing microphone. The scribed line on the white tape marks every 5 degrees in the circumference of the test circle.

Figure 31 The proximity to the wall and orchestra shell prompted many questions about the validity of the measurements from 65° to 90°.

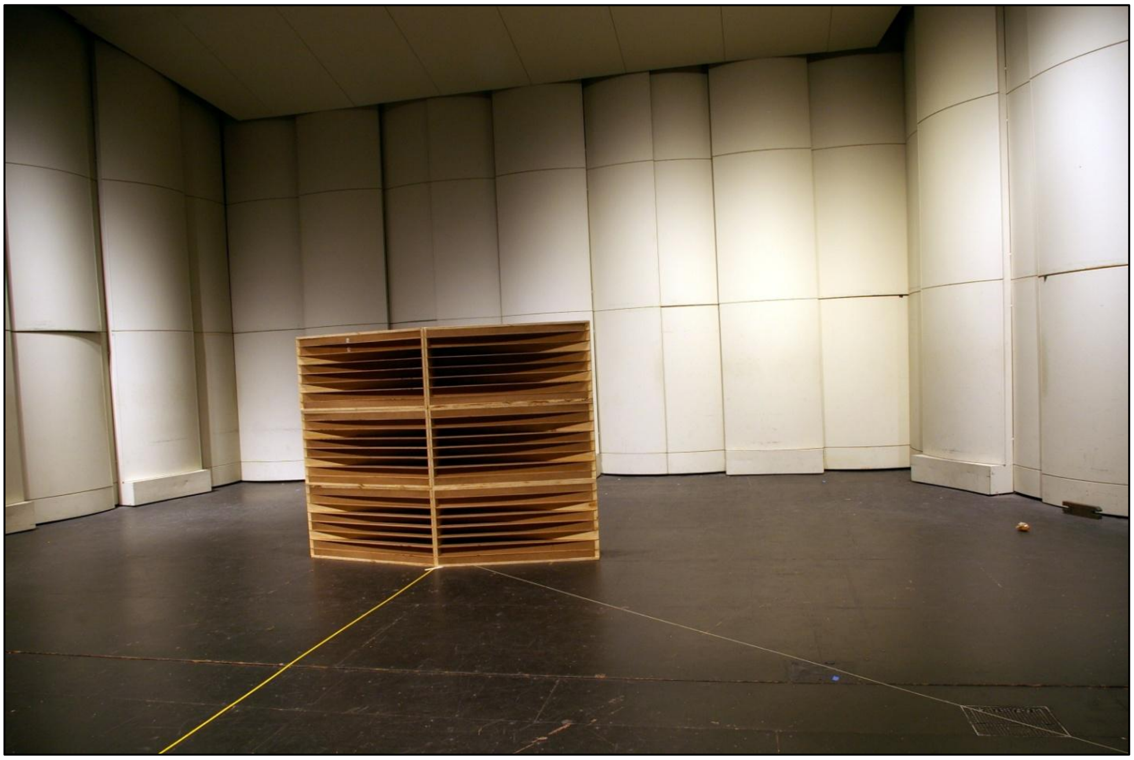


Figure 32 A six-diffuser array in horizontal position inside the testing circle

Figure 33 A Flat Panel array in testing position was created simply by reversing the diffusers under test and exposing the flat backs. The flat mounting bands of darker color and the slight differences in angle of the panels may have caused errors in the data collection.

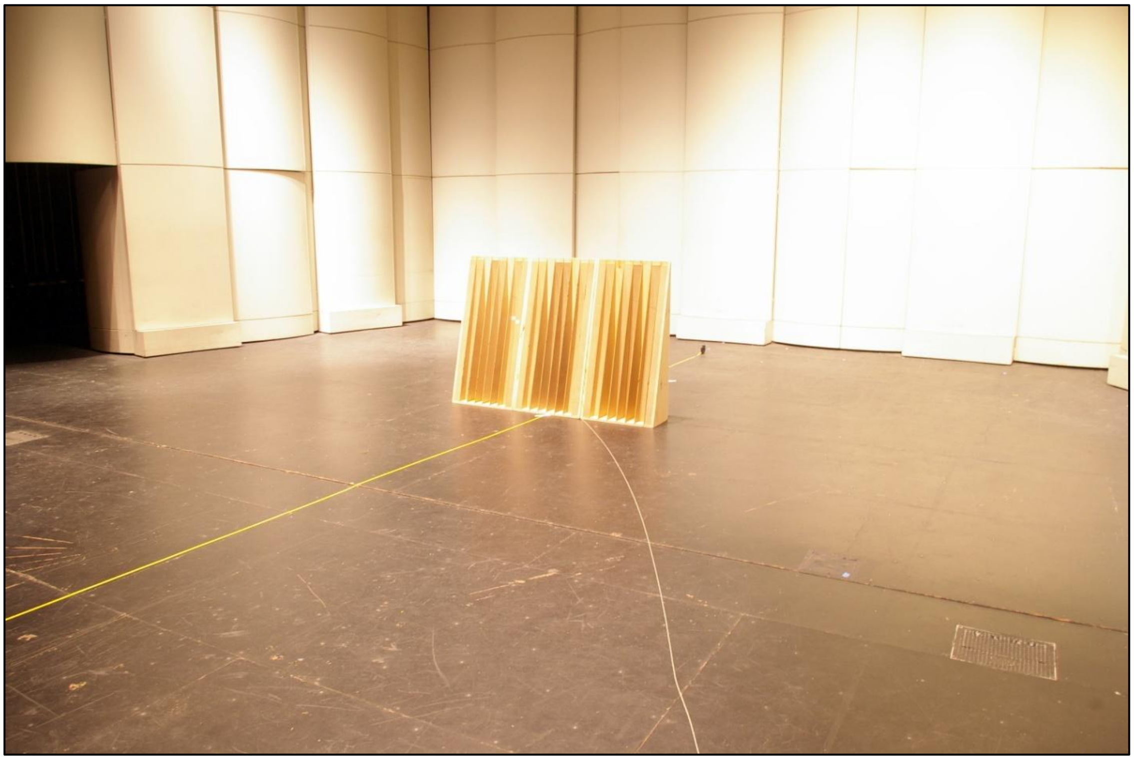


Figure 34 A three-diffuser array in the vertical position in the test location was another problem noticed in the first test session. Obviously there are only three diffusers being tested in the vertical orientation as opposed to six being tested in the horizontal position.

Figure 35 Full view of vertical testing showing the test speaker and the diffuser being tested.

Initial Results

The most important results of the initial round of testing dictated that a revised test procedure needed to be defined. Two major variables in the testing needed to be altered. First, the size of the test radius needed to be decreased to move the testing microphone locations further away from reflectors, in this case the performance shell. Decreasing the radius size would allow for much easier analysis of the impulse responses because reflections off of boundary walls will not be confused with reflections from the panels under test. Second, the array of ramps needed to be replaced with a single diffuser. The arrays complicated the extraction of data because the vertical and horizontal test positions required a different number of diffusers. The horizontal test position required a 6 diffuser array in order for the array to be symmetrical on the testing plane, while the vertical array only consisted of 3 diffusers. By using a single diffuser, all of the positions of the diffuser and the flat panel would be controlled and would have the same surface area in one plane.

Acoustic Ramp Test Session 2

Procedure

The second series of tests was more effective, valid and easier to interpret. The procedural changes made major improvements in the quality of the data that was acquired. The following specific changes were made in the testing methodology:

1. **Reduced the size of the test radius from 20 feet to 5 feet**

   Based on Alex Case's advice, the test footprint was reduced in size. The potential problems of unwanted reflections interfering with the initial scattering and first reflection were eliminated by reducing the size of the testing radius to only five feet. This was a reasonable change because the Mackie HR824 is a near-field monitor as is designed to be most accurate on axis and at short distances.

2. **Switched to dual-channel ARTA testing**

   By using a hardware feedback loop on one channel of the audio interface ARTA is able to synchronize the beginning of each impulse response to the same start point without regard to the distance of the microphone from the test loudspeaker. This ensures that the reflection from the test panel always arrives at the same position (time) in the deconvolved audio file, so gating and isolating the reflection for analysis is much easier.

3. **Reduced the object under test to a single Acoustic Ramp**

   I was able to improve validity and accuracy of the test by using a single diffuser to test with. In this way, both horizontal and vertical orientations of the diffuser are the same size unlike in the previous test session. This also greatly reduces the complexity of the testing procedure.

4. **Decoupled the loudspeaker from the floor with Auralex speaker isolation pads**

   Low frequency resonances and interference were reduced by decoupling the speaker from the stage floor.

Documented Procedure

The layout process of the test field was dramatically easier with a smaller radius. The location of the loudspeaker was maintained, but the center of the test circle was repositioned closer to the loudspeaker and the location of the testing arc was redrawn.

Figure 36 through Figure 39 show the revised layout of the test field. The process of scribing the test field onto the stage floor was very similar to the process used in the first battery of tests. After the stage was bisected with the yellow construction string, the quarter circle was defined by adding a white construction string line perpendicular to the yellow string. The 90° angle was verified using trigonometry and the microphone test positions every 5°were marked onto white tape strips using similar math. The positions of the tape were approximate, but the crosshairs marked onto the tape were exact.

The diffusers were placed with the rear wall of the diffuser aligned to the center of the test circle, so that the wells, reflectors and dividers protruded into the test circle. The flat reflector was formed by using the rear of the diffuser under test (see Figure 41). In the case of the vertical orientation of the diffuser, the diffuser is placed onto the center point of the test circle (see Figure 42). In the case of the horizontal orientation of the diffuser the vertex of the diffuser is placed on the center of the test circle (see Figure 45).

The difference in location between the vertical and horizontal location of the diffuser under test exposes a sort of problem in the symmetry of the test. In order to increase the consistency of the vertical and horizontal tests, the 3 and 6 diffuser arrays were abandoned in favor of using a single diffuser for both orientations. This dictated that the object under test in the horizontal orientation was no longer symmetrical, so the horizontal diffuser was oriented as if it was part of a symmetrical 2-diffuser array with the vertex of the diffuser on the center point. In this way, the validity of collecting only a quarter circle of data was maintained.

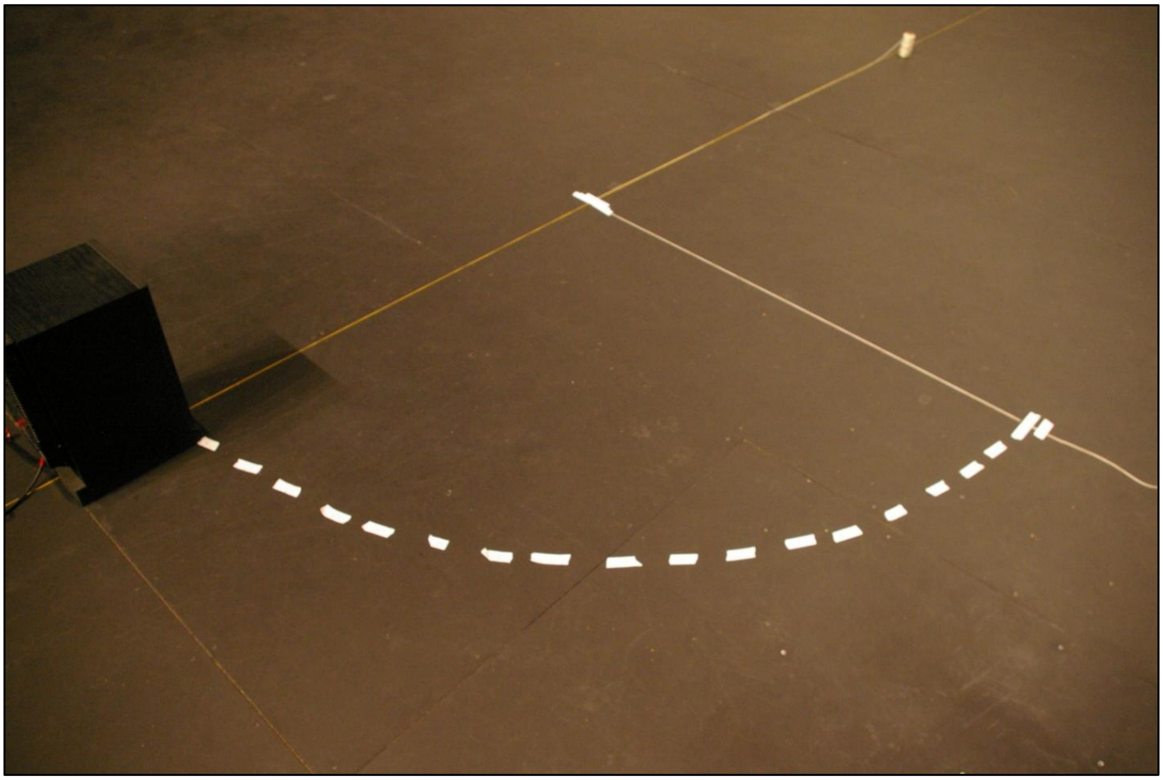


Figure 36 The 5' radius testing setup. White tape marks the 5 degree increments. 90 degree mark was verified using $a^2 + b^2 = c^2$ formula.

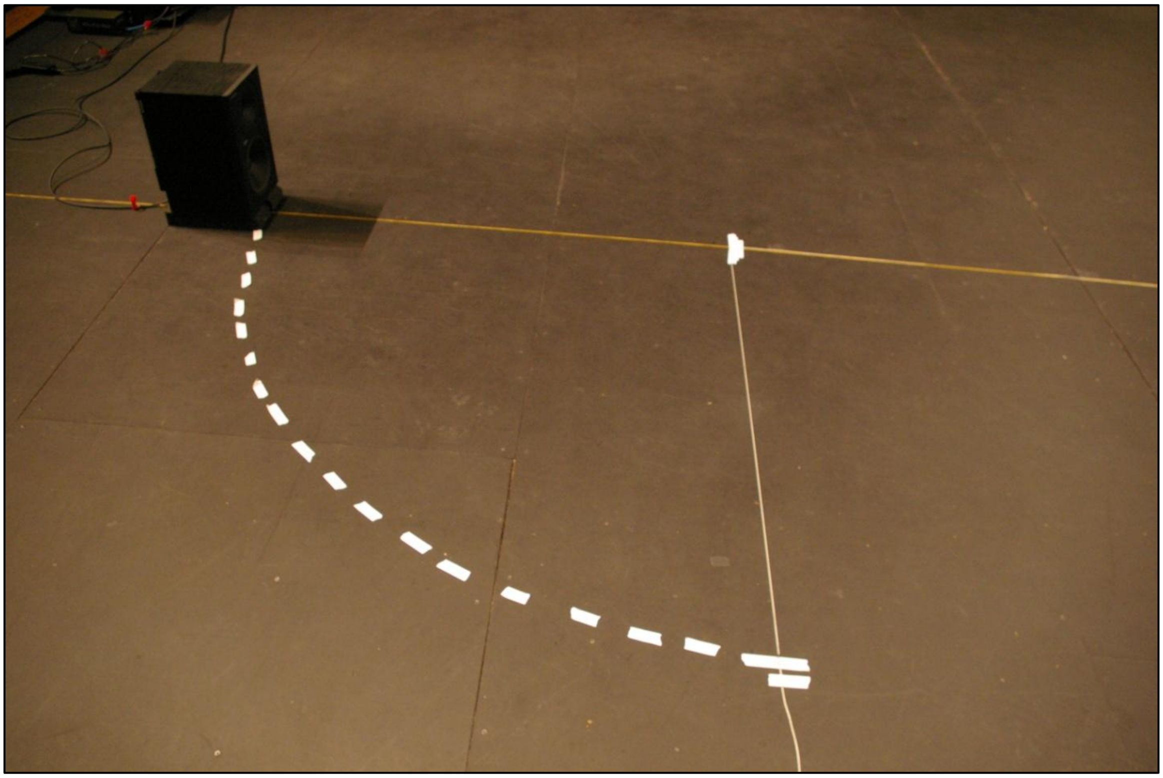


Figure 37 A second view of the 5' radius testing setup.

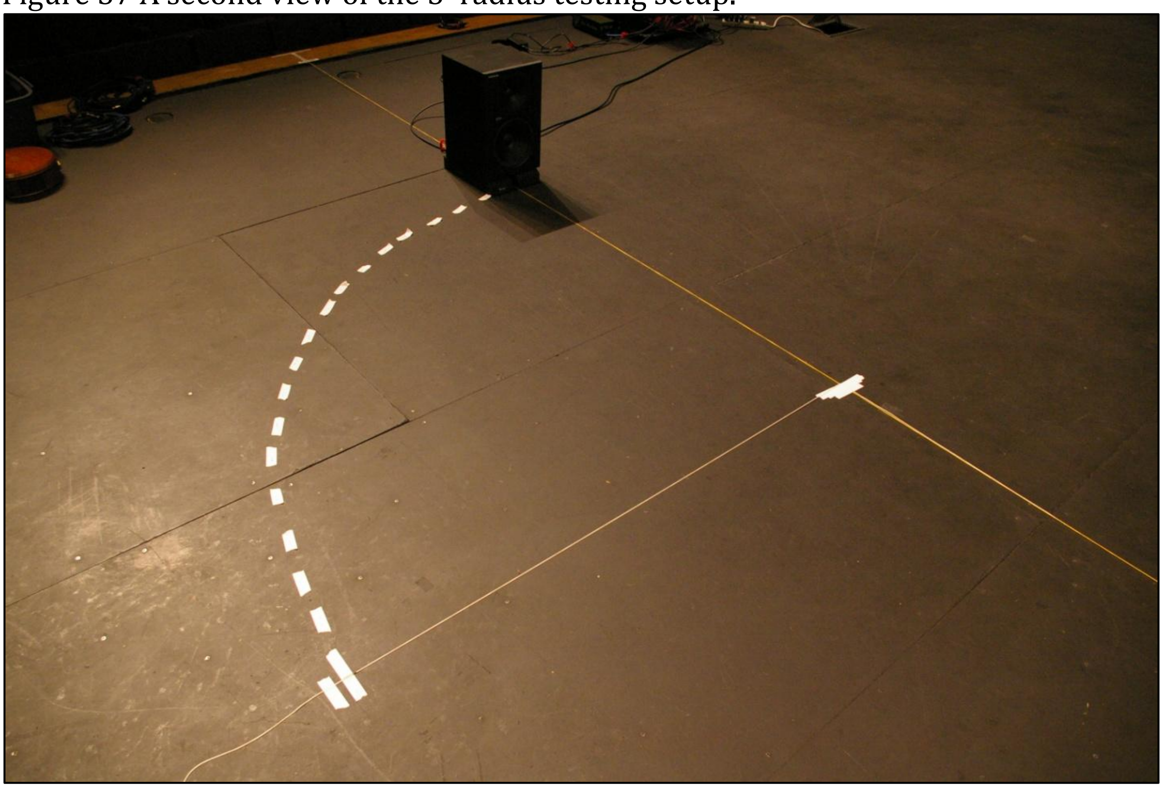


Figure 38 A third view of the 5' radius testing setup.

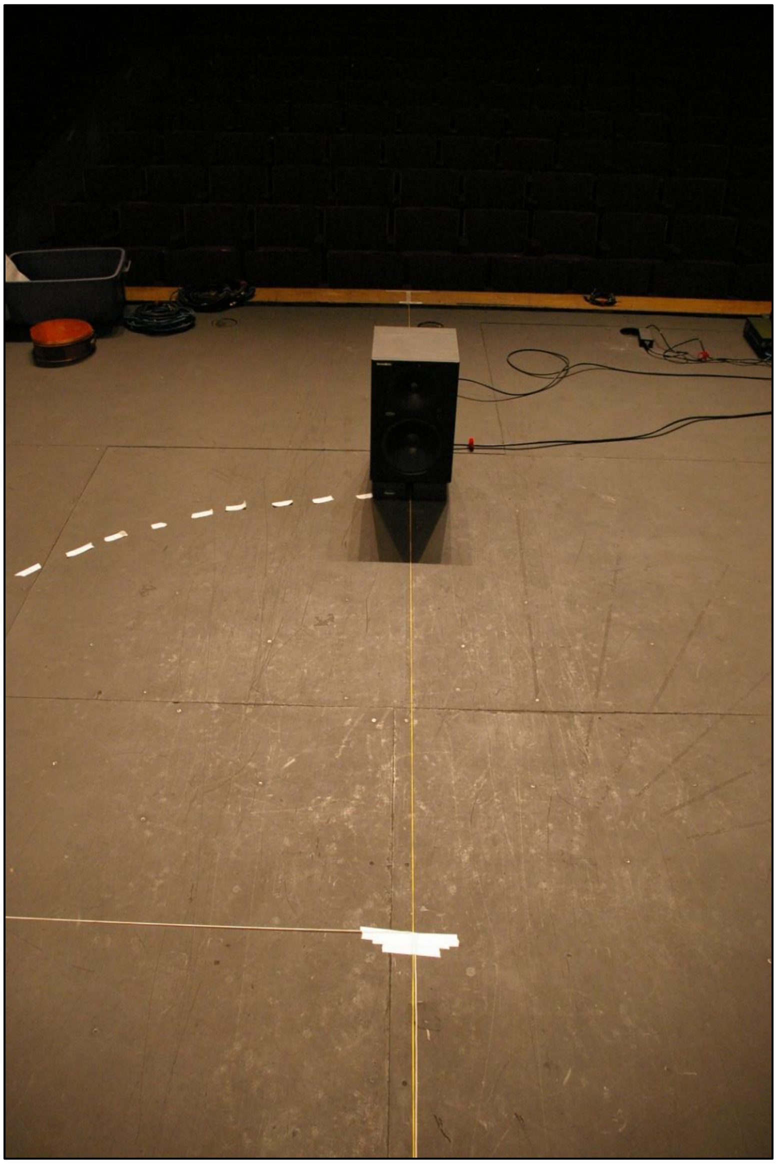


Figure 39 A fourth view of the 5' radius test setup

Figure 40 Testing hardware system. Windows XP laptop using ARTA acoustic testing software, a MOTU Traveler, and a Daking Audio Mic Pre One.

Figure 41 Testing a flat panel in the vertical orientation with the 5' radius testing setup.

Figure 42 Testing an Acoustic Ramp diffuser in vertical position using the 5' Radius testing setup.

Figure 43 A second view of testing the Acoustic Ramp in the vertical orientation.

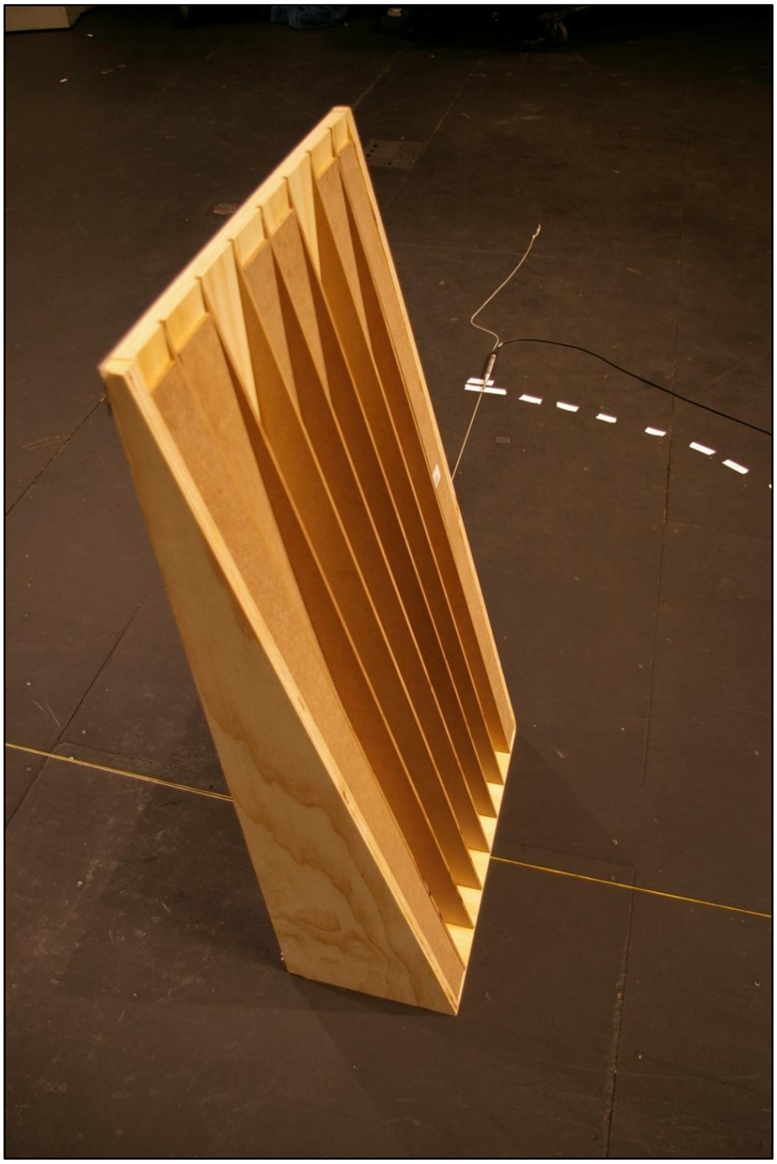


Figure 44 A third view of testing the Acoustic Ramp in vertical orientation.

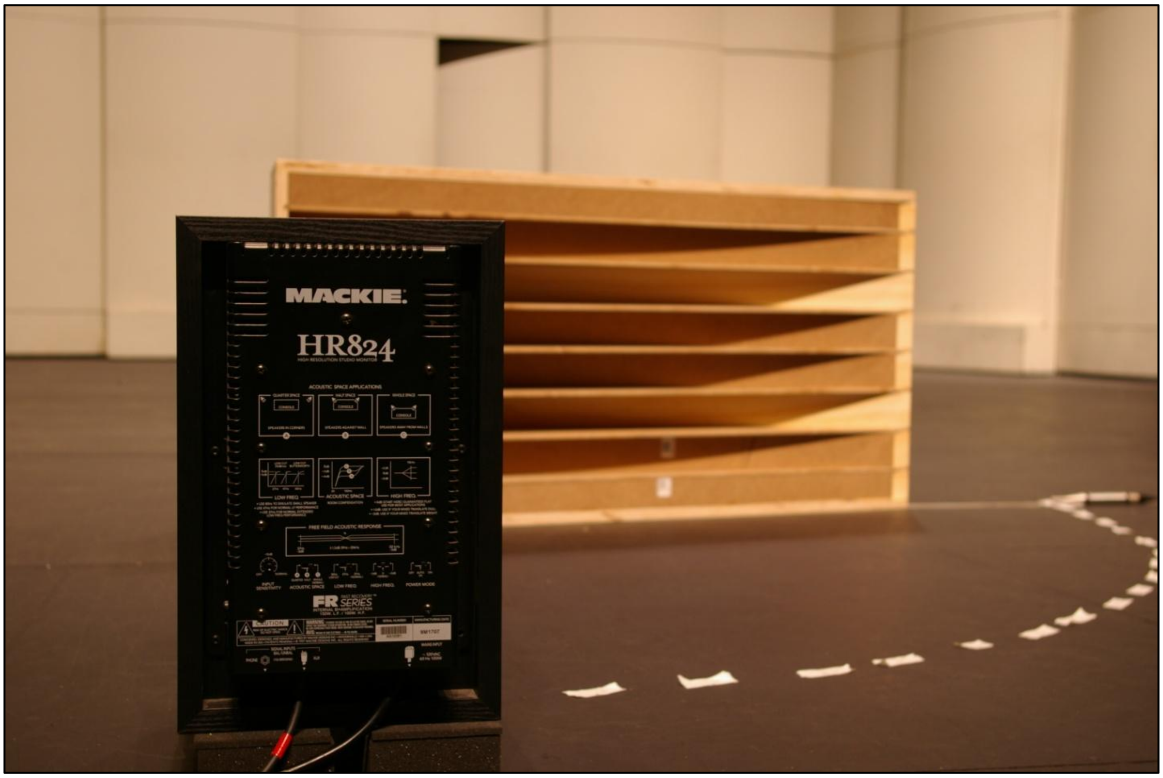


Figure 45 Testing the Acoustic Ramp in horizontal position in the 5' radius testing setup.

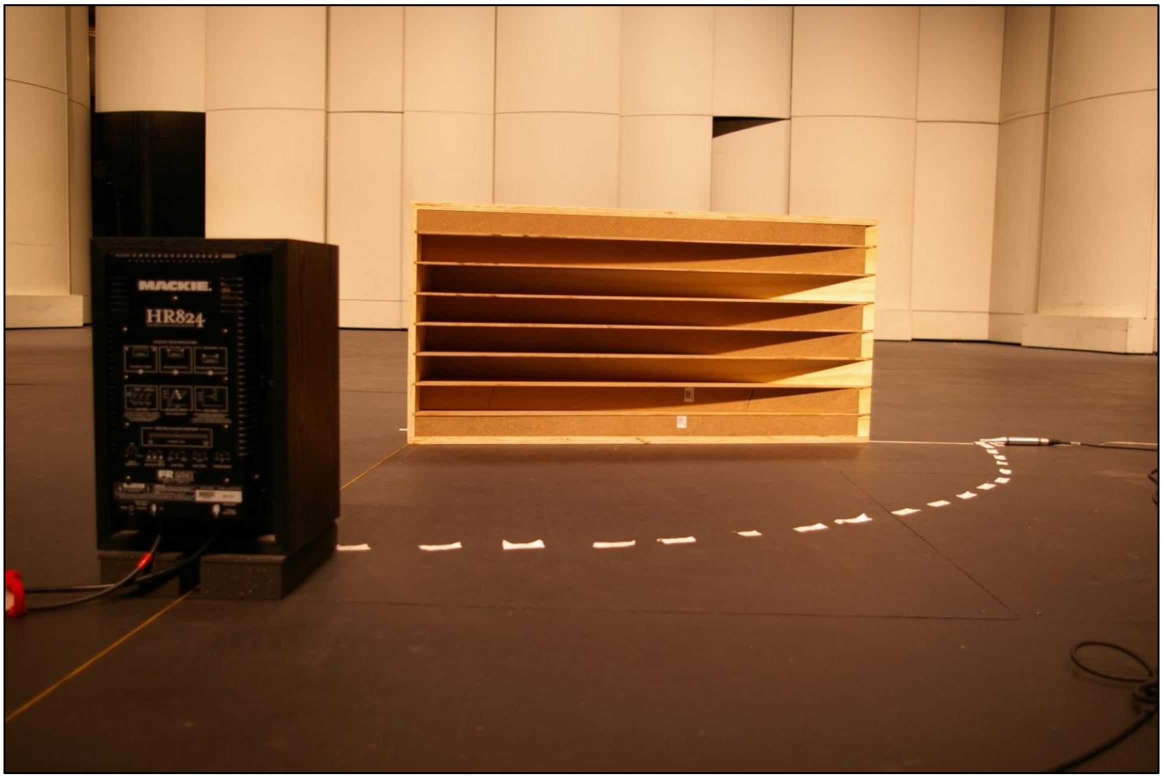


Figure 46 A second view of testing the Acoustic Ramp in horizontal orientation.

Limitations to the Session 2 Tests

1. Flat panel had two mounting plates screwed to the wood which could have caused diffusive behavior.
2. The test radius is too small for certain frequencies. 5 feet has a low frequency boundary of 226 Hz. This is below the anticipated effective frequency of 282.5 Hz. so this should not be a significant problem.
3. Earthworks TC-25 isn't a true PZM microphone and didn't lay perfectly flat on the floor so there may be some minimal phase issues from floor reflection. Distance from the edge of the diaphragm to the floor was .317" or .02641' which corresponds to quarter-wavelength of 10.7kHz.

RESULTS

Understanding the Data

The raw data from the tests was prepared visually as both sonograms and as polar distributions. Each of the tests was repeated to eliminate possible problems from intermittent background noises or equipment anomalies. The sonograms have a 1/12th octave granularity from 50 Hz to 20,000Hz which is more detailed that the more commonly employed 1/3 octave data. The polar distributions detail a single frequency per plot. The data should not be considered reliable below 225 Hz or above 10kHz because of distance from the loudspeaker and the diffuser and the distance between the microphone capsule and the floor of the test field. The data beyond these frequency boundaries are included in the sonograms in the interest of obtaining a complete picture of the test results.

Polar Response and Sonogram charts are typically shown depicting a semicircle (180°) of directivity data. It should be noted that the horizontal diffuser tests were made with an asymmetrical orientation of the diffuser, but with the vertex of the diffuser placed on the center point of the test circle. In the case of both the vertical and horizontal testing, only one quarter of the circumference was tested. In the case of the horizontal orientation sonograms, the other quarter is shown as if the diffuser was symmetrical, copying the response from one quadrant to the other. In the case of the polar response plots, only the tested quarter is depicted.

In order to produce the following images from the raw impulse response data, the impulse response needed to be time gated to eliminate the non-essential audio data and remove the sounds both before and after the desired reflections reached the testing microphone. All of the impulse responses have been gated from 10 ms to 15ms and only the data from inside that time period is used to assemble the SPL measurements from which the directivity charts are generated. Unfortunately, the 5 ms window size limits the accuracy of the testing to frequencies above 226 Hz. Frequencies below 226 Hz cannot be properly evaluated because one cycle is actually longer than 5 ms.

Sonogram Results

Flat Panels

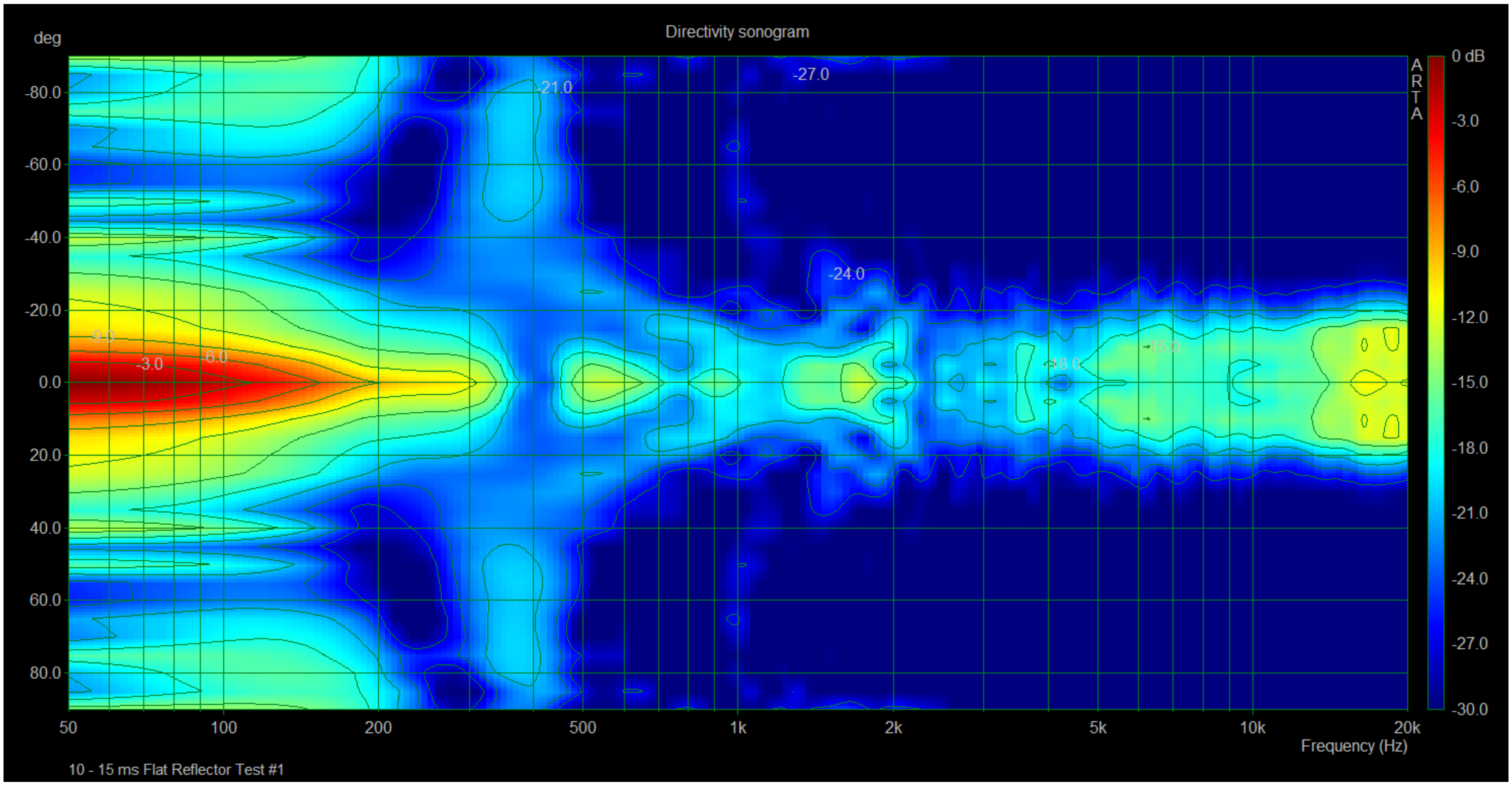


Figure 47 Sonogram from Flat Panel Test #1

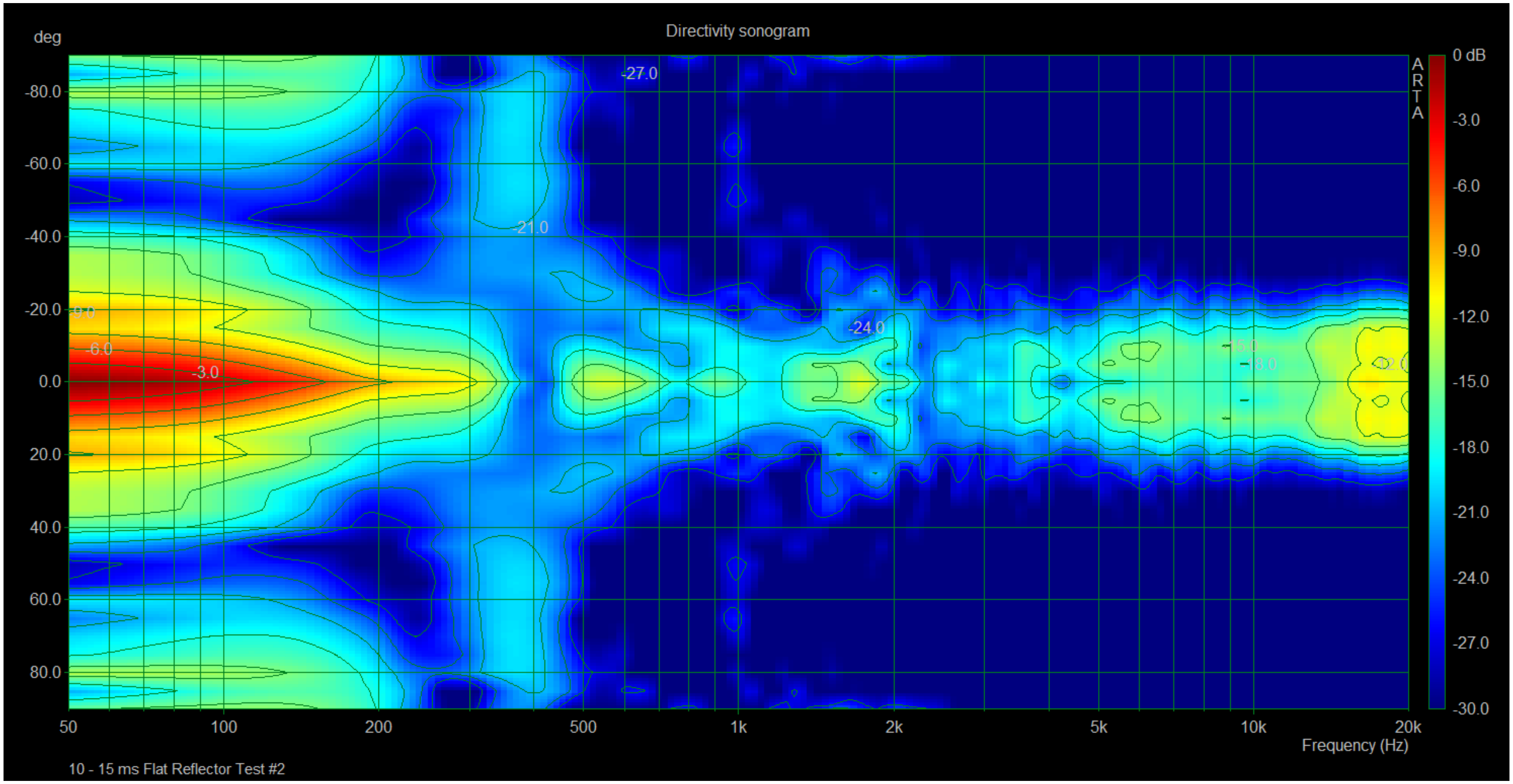


Figure 48 Sonogram from Flat Panel Test #2

Interpreting the Flat Panel Sonograms

Understanding the reflection behavior of the flat panels is critical to understanding the reflection behavior of the diffusers because the flat panels are the control group against which the diffusers are measured. As mentioned before, the test is invalid below 226Hz because the gated window of the impulse response is only 5 ms. The upper bandwidth is defined by the distance of the test microphone capsule from the floor which yields an approximately 10kHz boundary. The central hotspot and horizontal striped appearance of the sonogram from 50 - 300 Hz is indicative of artifacts of the testing procedure.[18] The diffusive behavior centered around 400 Hz is consistent with the behavior of flat panel edge effects. [18] The majority of the acoustic energy lies in the range from -20° to +20° which is the spectral zone as defined by the distance between the loudspeaker, the panel, the microphone and the size of the panel. [13] This topic is developed more in the section "Diffusive Behavior of Flat Panel and d_ψ Normalization" later in this paper.

Diffusers in Vertical Orientation

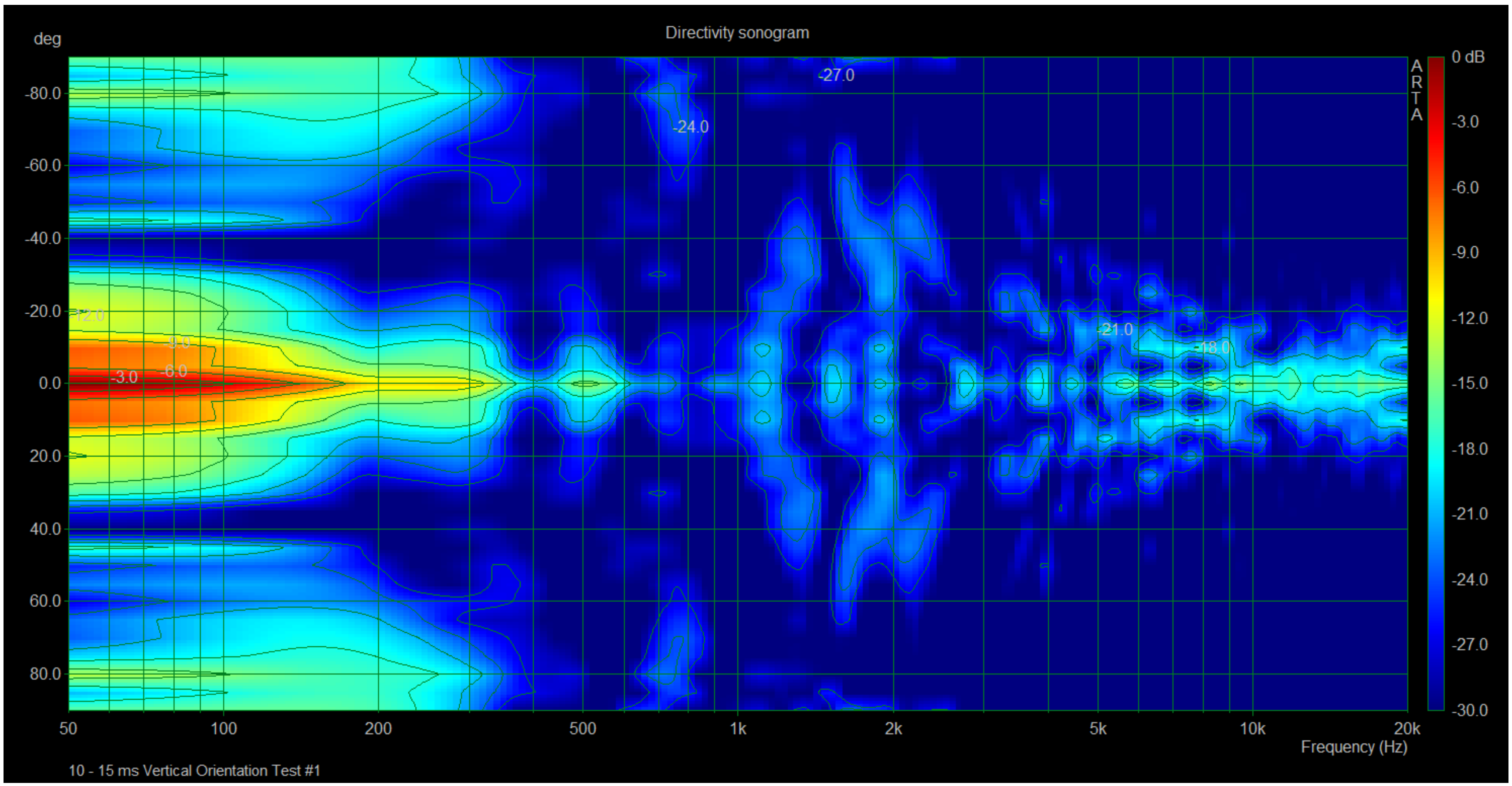


Figure 49 Sonogram of the Vertical Diffuser Test #1

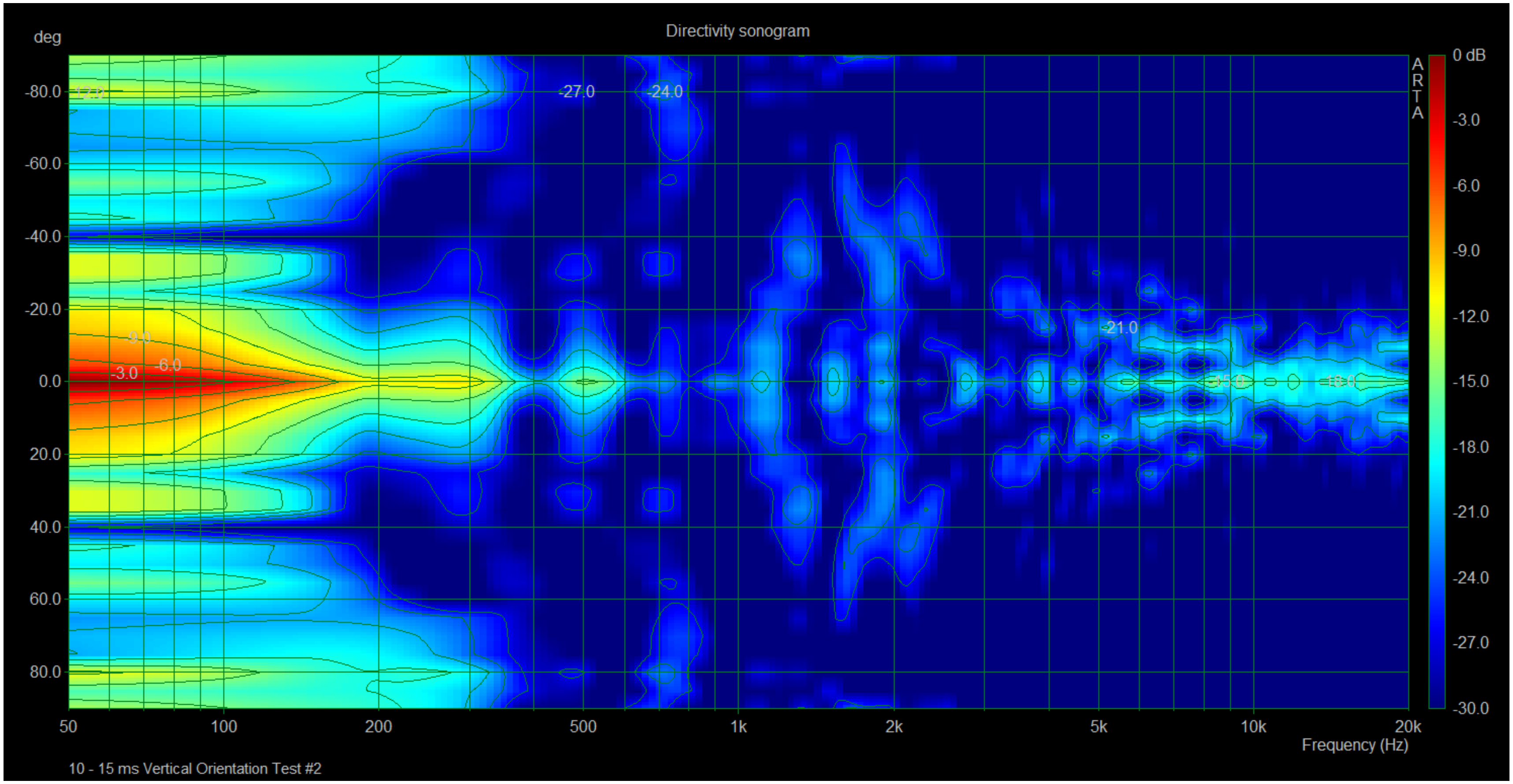


Figure 50 Sonogram of the Vertical Diffuser Test #2

Interpreting the Vertical Orientation Sonograms

As with the previous test, the frequencies below 226Hz and above 10kHz are not considered to be reliable. What is evident from the sonogram, is the removal of the spectral hot spots from the 400 Hz to above 5kHz. The more uniform the vertical color temperature, the more effective the diffuser is at scattering at that specific frequency. While there is an apparent hotspot at 0°at 500 Hz, the diffusion pattern is clearly improved over the flat panel's pattern. Although the scattering behavior gets narrower as the frequencies increase as they ascend from 1kHz to 10kHz, the response is still clearly improved over the flat panel. The color temperature is dramatically decreased even in the most spectral parts of the frequency response. There is an overall reduction in the amount of reflected energy compared to the flat panel because the diffuser is also scattering the energy up off the stage floor away from the microphone. It is important to note that while the vertical striping of green/light blue between 1kHz and 2kHz looks very promising, the vertical stripes of dark blue at 400Hz, 600Hz and 3kHz are *also* demonstrating excellent diffusion just at a lower intensity.

Diffusers in the Horizontal Orientation

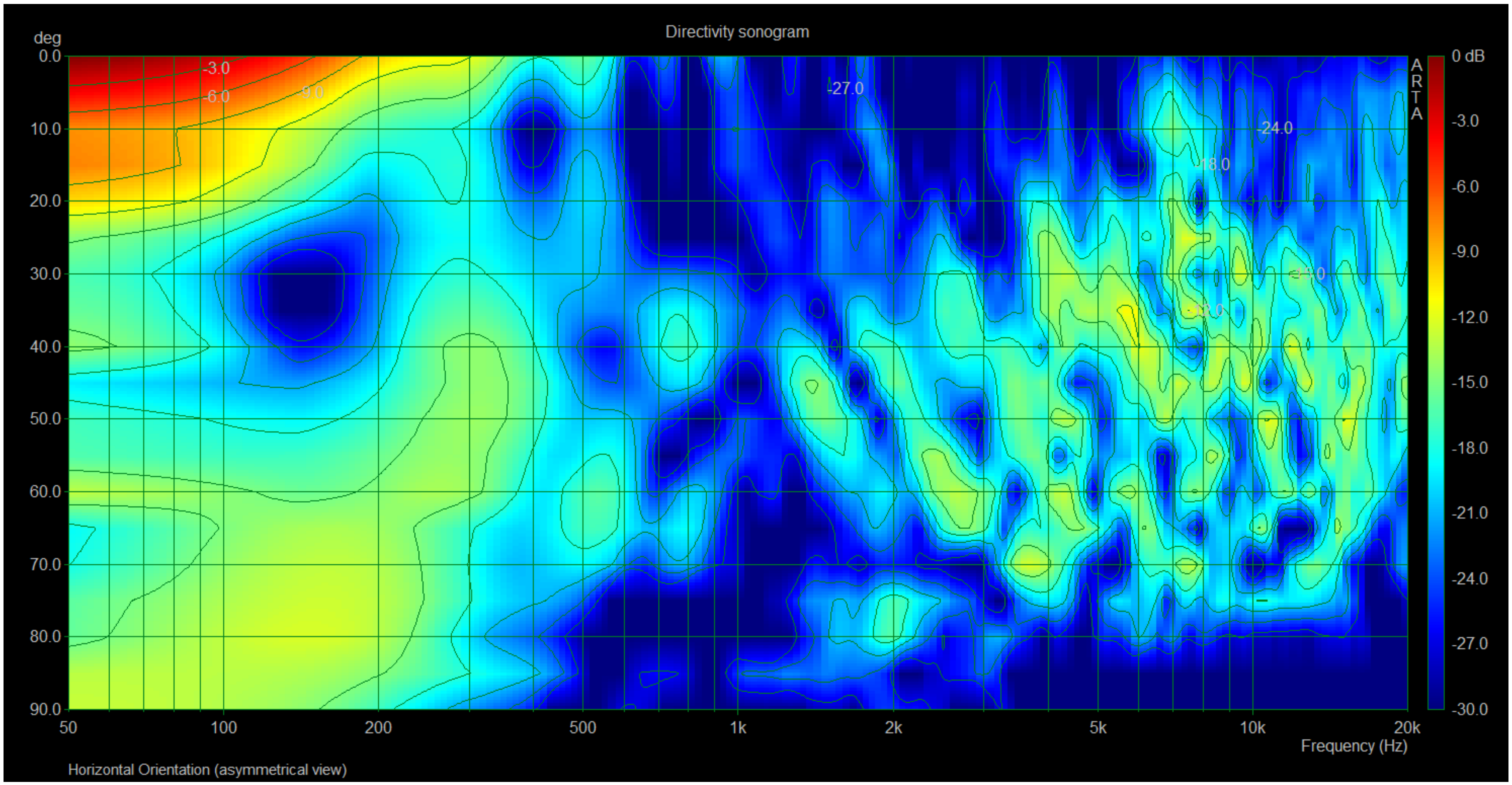


Figure 51 An asymmetrical sonogram from a horizontally oriented diffuser test. The image is not forced symmetrical in order to emphasize the lack of symmetry in the horizontal test.

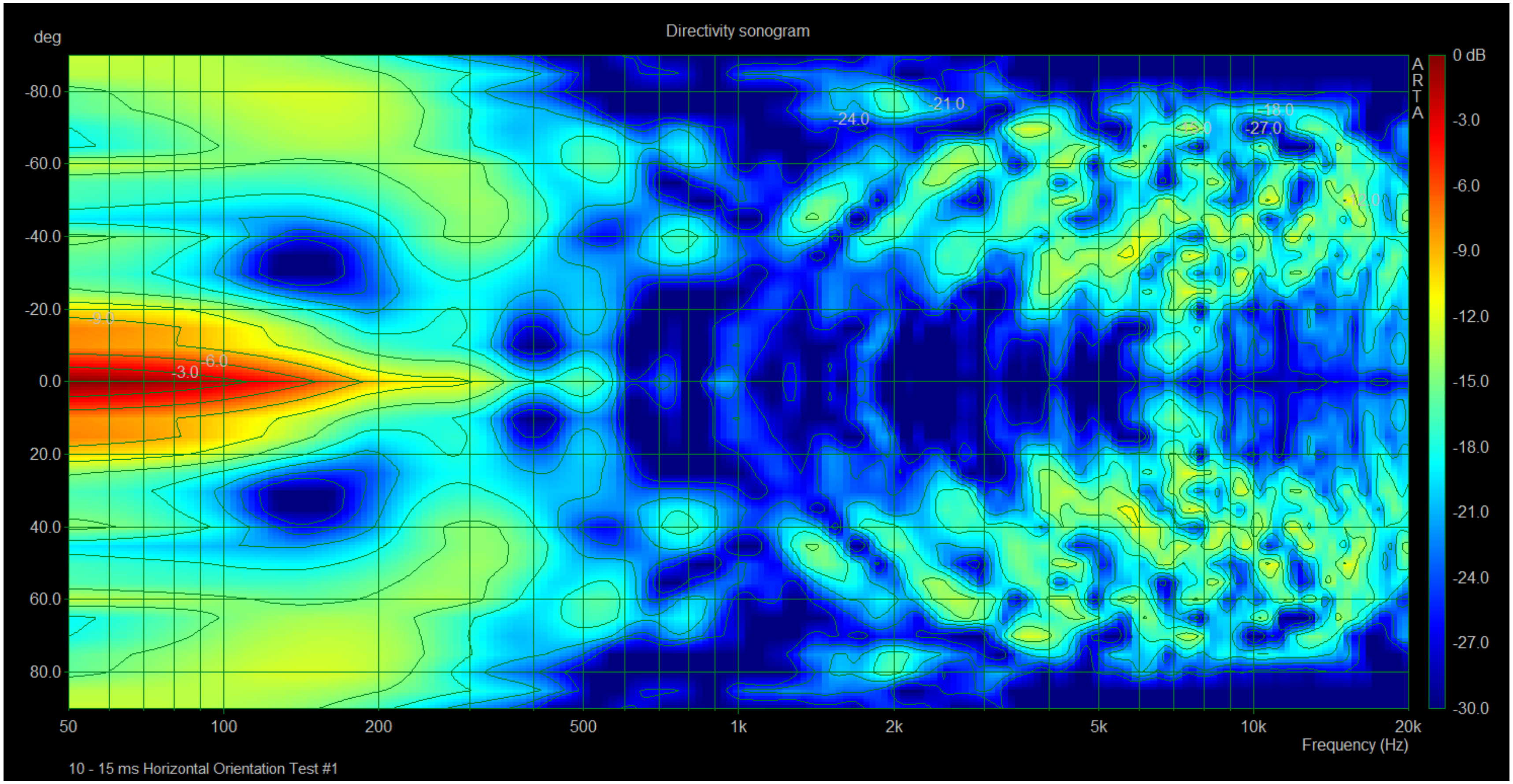


Figure 52 Sonogram of the Horizontal Diffuser Test #1. This sonogram and the following sonogram have been adjusted to look symmetrical for the purposes of comparison to the symmetrical sonograms from the vertical diffuser and flat panel.

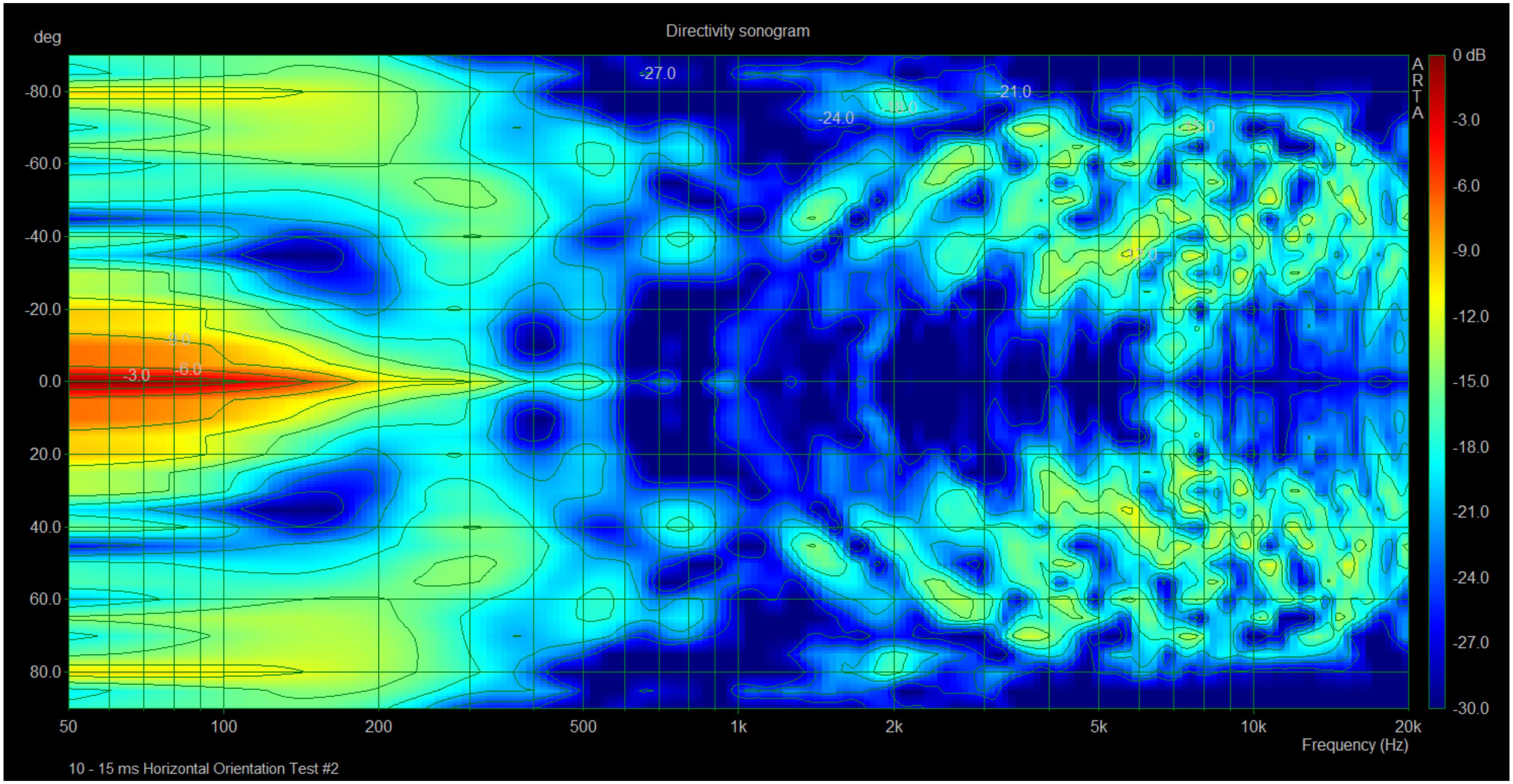


Figure 53 Sonogram of the Horizontal Diffuser Test #2

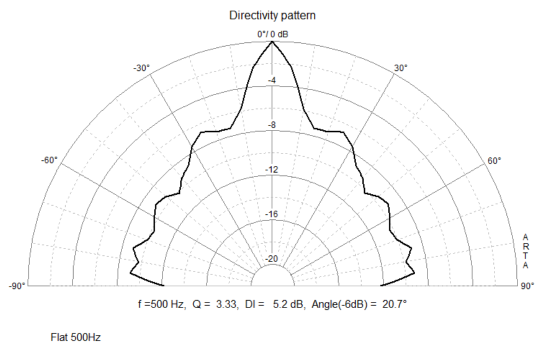
Interpreting the Horizontal Orientation Sonograms

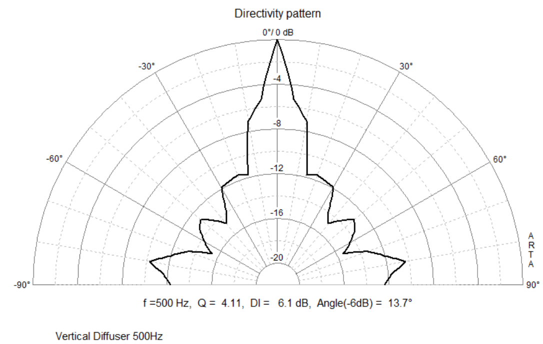
As with the previous tests, the frequencies below 226Hz and above 10kHz are not considered to be reliable. The most striking feature of these sonograms is how they are very nearly the inverse of the spectral reflections. Reflected energy is staying out of the center of the field and is spreading fairly evenly from 20° to 80° in the frequencies above 500Hz. The scattering response is markedly different from the vertical scattering in that there are numerous hotspots outside of the spectral zones. Looking at polar distributions these hotspots would appear as the lobing of specific frequencies at specific locations.

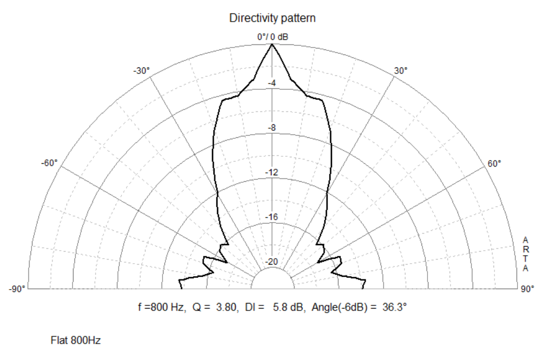
Polar Response Comparisons

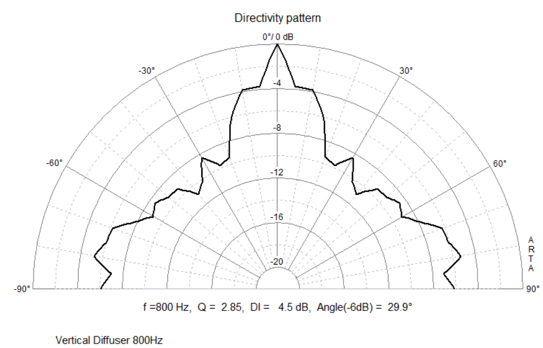
The follow polar responses have been included to be backward compatible for readers who are unfamiliar with the more comprehensive sonograms. As mentioned before in the "Visualizing Data from Diffusion Testing" section, polar distributions are extremely useful for evaluating and comparing surfaces as a specific frequency. The very fact that there is less information in the polar distributions is exactly what makes them more useful for direct comparisons between the directivity of two or more surfaces.

<table>
<tr><th>Flat Panel</th><th>Vertical Diffuser</th></tr>
<tr><td>500 Hz


</td><td>500 Hz


</td></tr>
<tr><td>800 Hz


</td><td>800 Hz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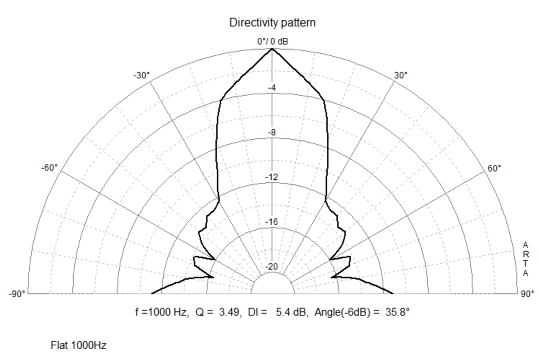
<tr><td>1000 Hz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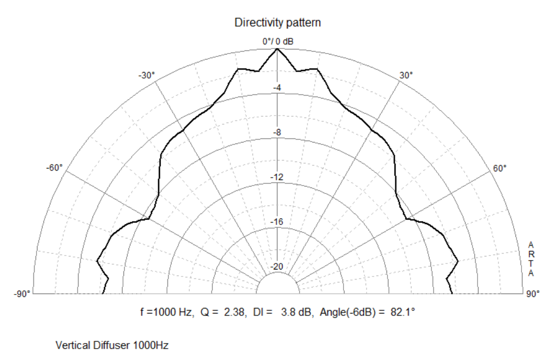
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<table>
<tr><th>Flat Panel</th><th>Vertical Diffuser</th></tr>
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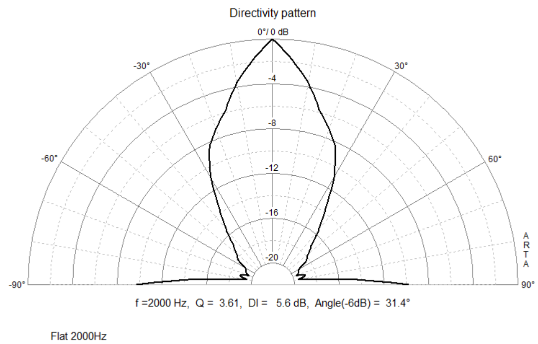
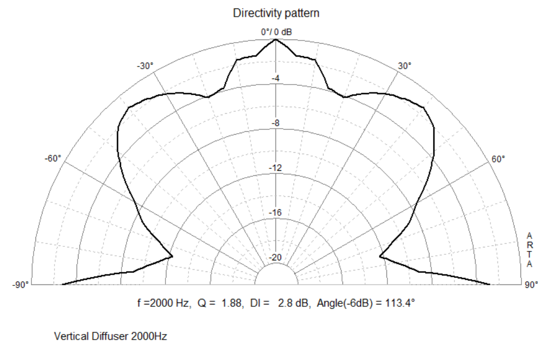
</td><td>2000 Hz
</td></tr>
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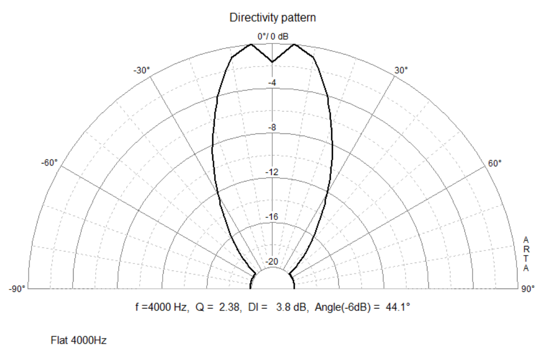
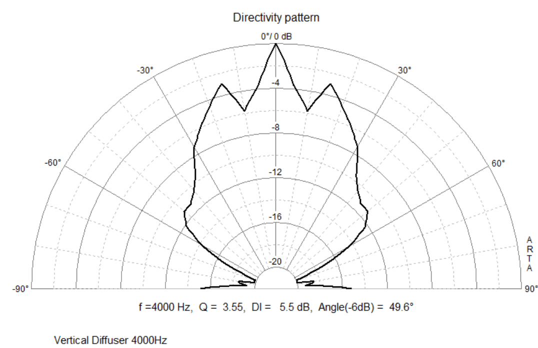
</td><td>4000 Hz
</td></tr>
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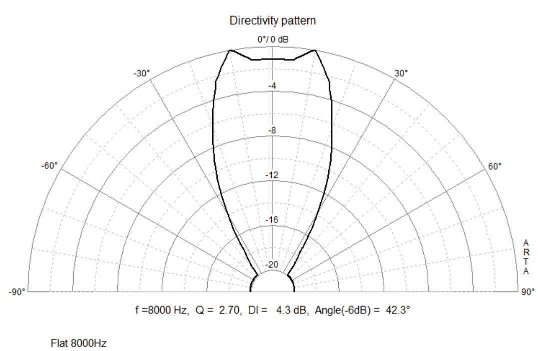
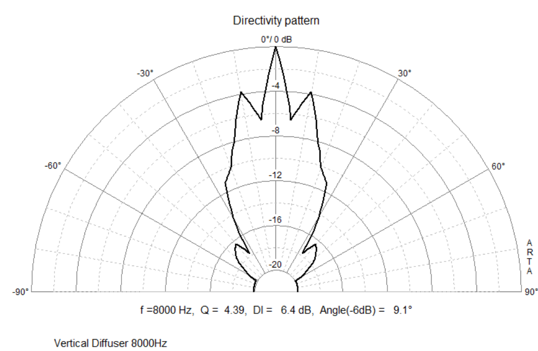
</td><td>8000 Hz
</td></tr>
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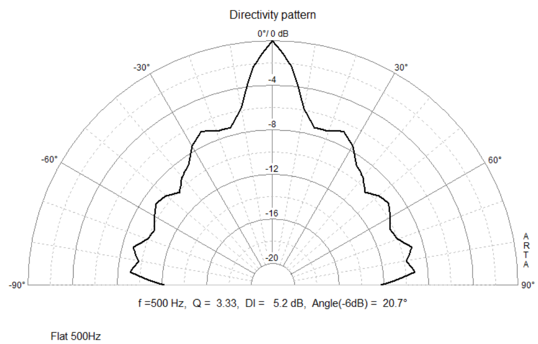
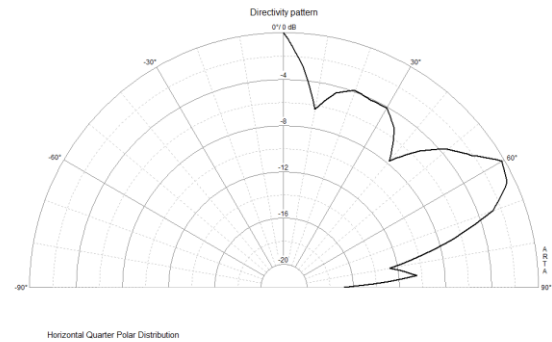
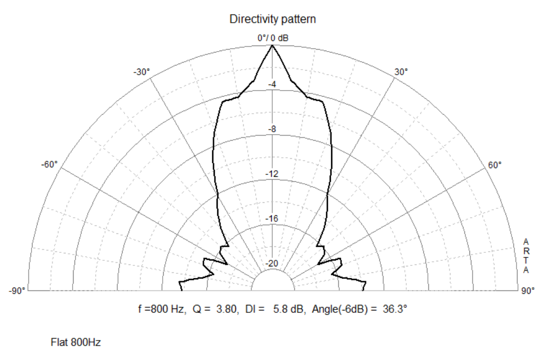
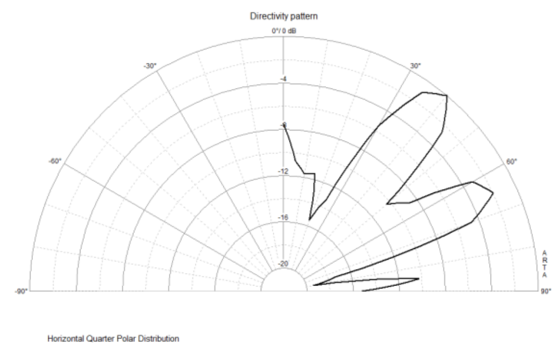
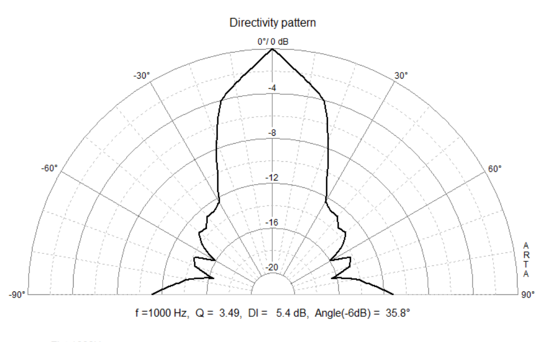
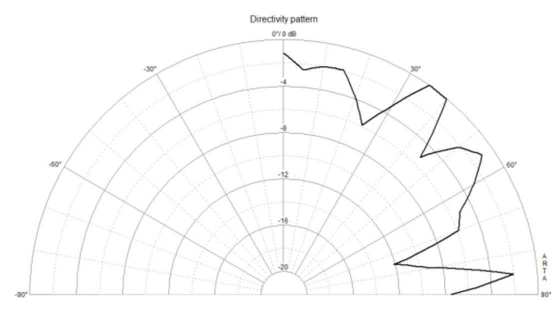
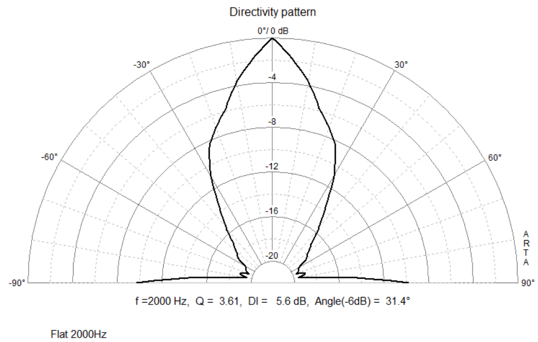
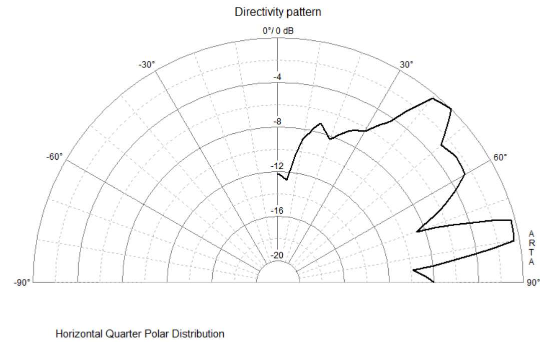
Flat Panel	Horizontal Diffuser
500 Hz 	500 Hz 
800 Hz 	800 Hz 
1000 Hz 	1000 Hz 

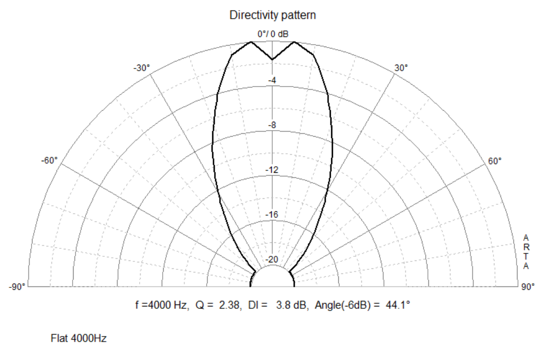
2000 Hz



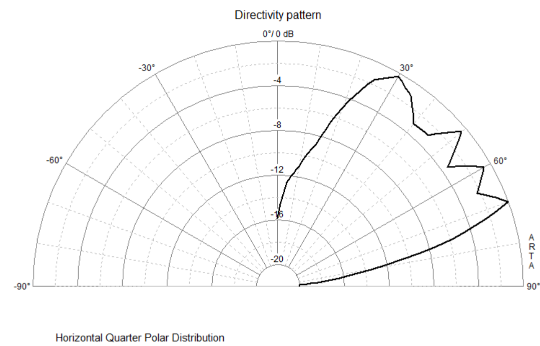
2000 Hz



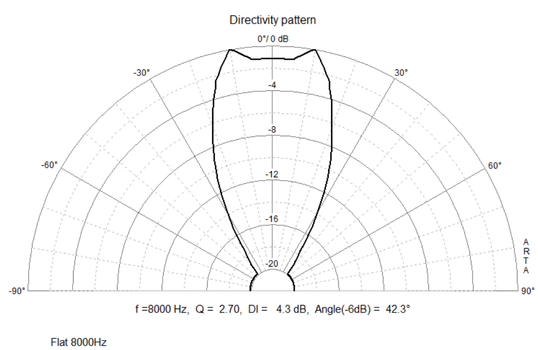
4000 Hz



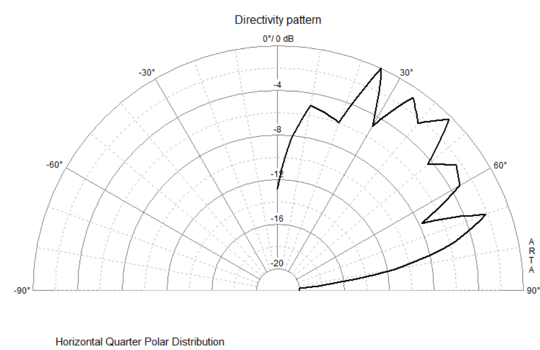
4000 Hz



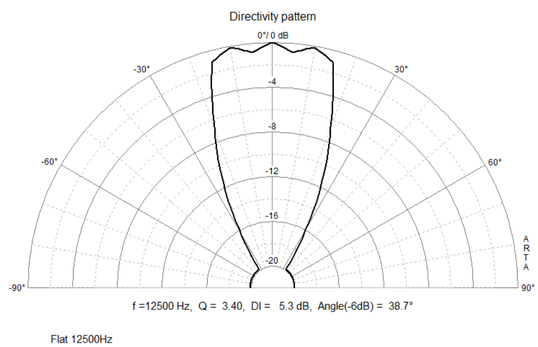
8000 Hz



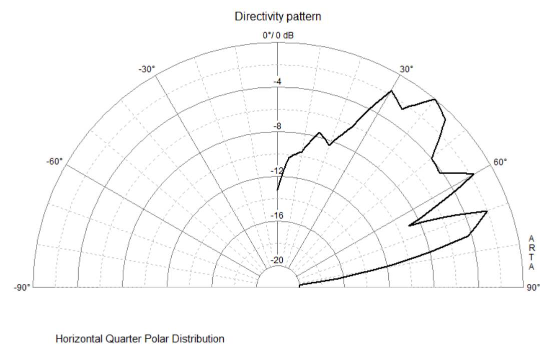
8000 Hz



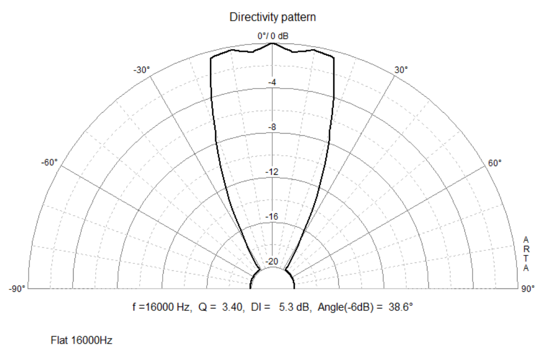
12,500 Hz[2]



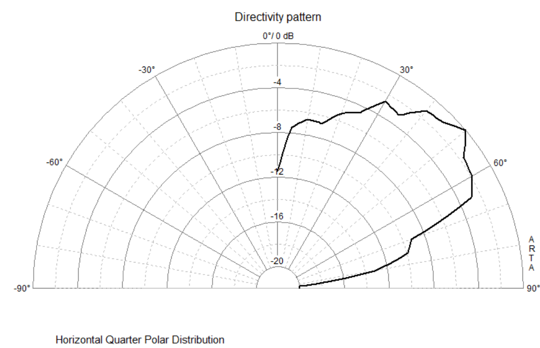
12,500 Hz



18,000 Hz



18,000 Hz



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[2] 12,500 and 18,000 Hz are included for informational purposes only. These frequencies are above the calculated reliable frequencies.

Time Domain Performance

There is a tendency to focus analytical energies on the amplitudes of frequencies that are reflected from the diffusers and the flat panels. The diffusers actually increase the complexity of the time domain response in addition to physically spreading the energy across a larger distribution of space. Logically when sound strikes a flat surface, we expect that the reflected sounds will all bounce back at the same time. If the flat surface were to be split into several different parallel planes, it stands to reason that the additional distance that the sound needs to travel will cause an additional delay to the reflection. This is part of the manner in which a traditional 1D QRD diffuser works, especially if the diffuser lacks well dividers. The well dividers increase the complexity of the delay further because the sound waves reflect from the well dividers as well as the rear reflectors as they attempt to escape through the open face of the diffuser. Each reflection absorbs energy and the energy emerges from the diffuser diminished in amplitude, delayed in time and altered in direction.

There are several ways of visualizing time domain information. The easiest and most familiar of these is to view the impulse response waveform from acoustic testing as a waveform. Time and amplitude are both clearly shown in this format and with overlays two or more waveforms can be easily compared. The waveform shows the electrical analog of the air pressure at the location of the microphone during the test. Positive pressure is shown with positive voltage above the center line of the scope view and negative pressure is shown with negative voltage below. Time moves left to right with the earliest events to the left and later events to the right (see Figure 54 below).

By using overlays (Figure 55) or offset overlays (Figure 56) two waveforms can be compared easily visually. Transient points with a large sudden amplitude can be compared across the time domain.

Time Domain Waveform Diagrams

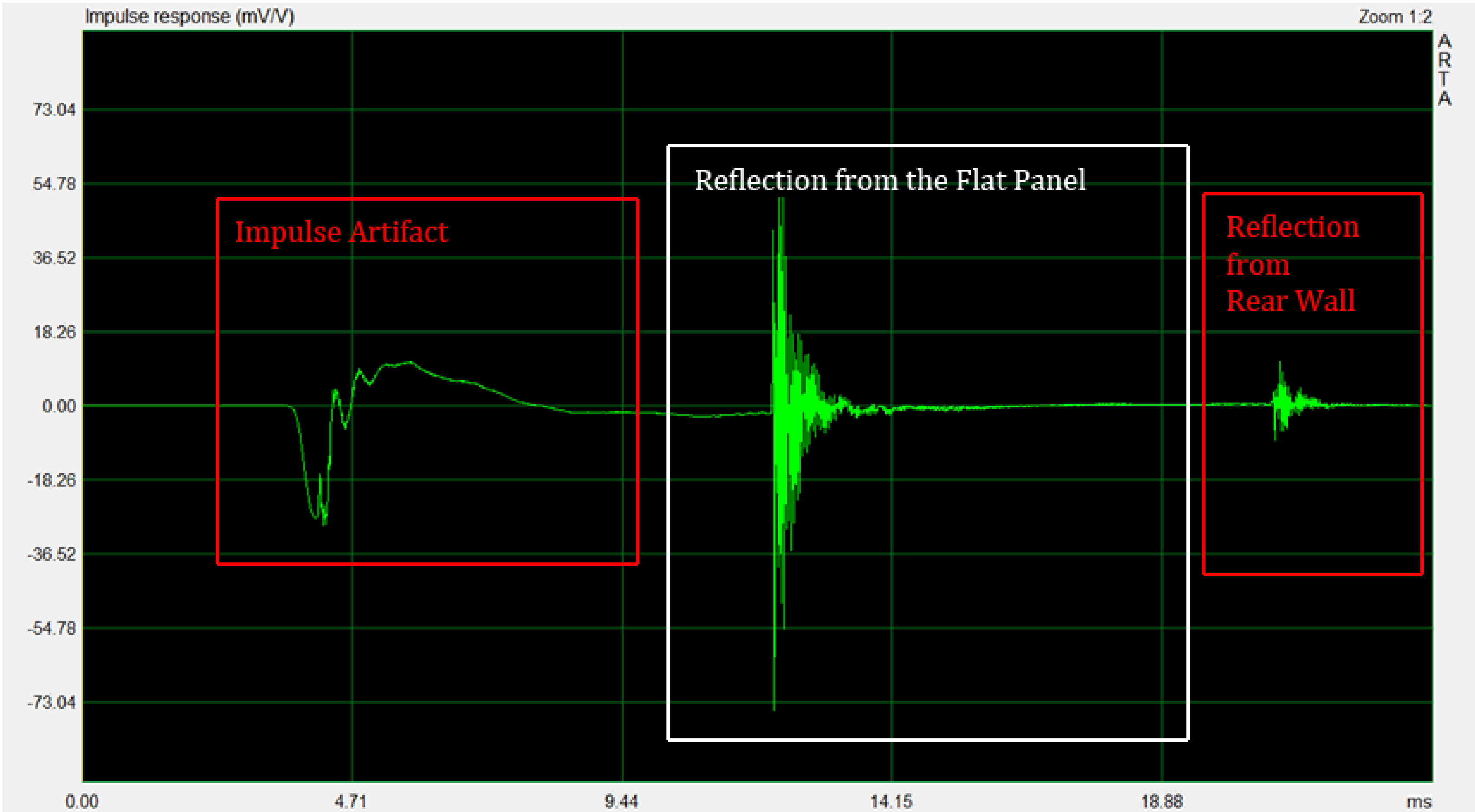

Figure 54 A specular reflection (highlighted in white) from the flat panel at zero degrees. The impulse artifact in the left part of the window is highlighted in red as is the reflection from the rear wall of the test field.

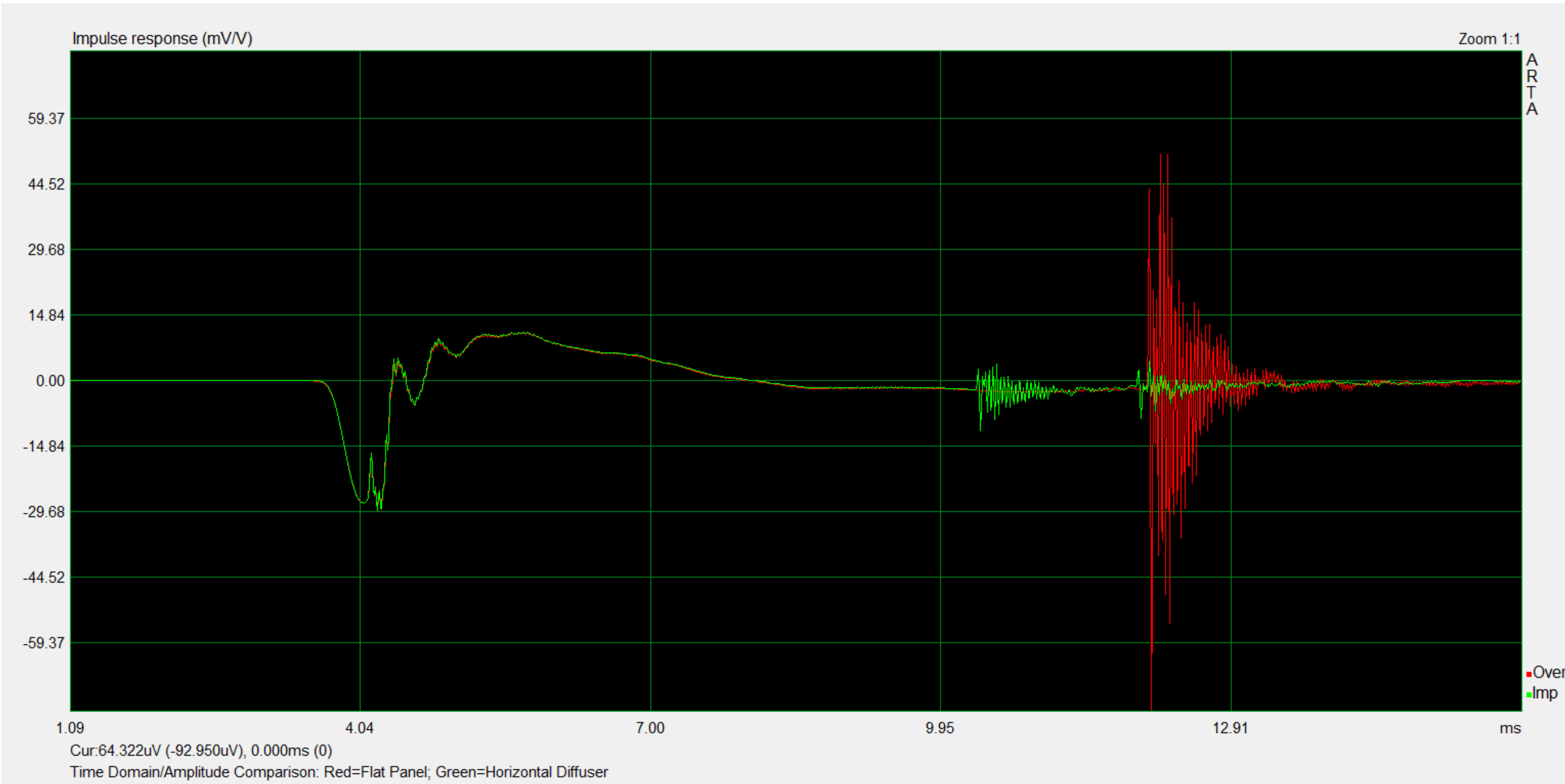

Figure 55 This waveform diagram with overlay allows for two waveforms to be compared easily across the time domain. In this diagram the red trace represents the response from a flat reflector while the green trace represents the response from a horizontally oriented diffuser.

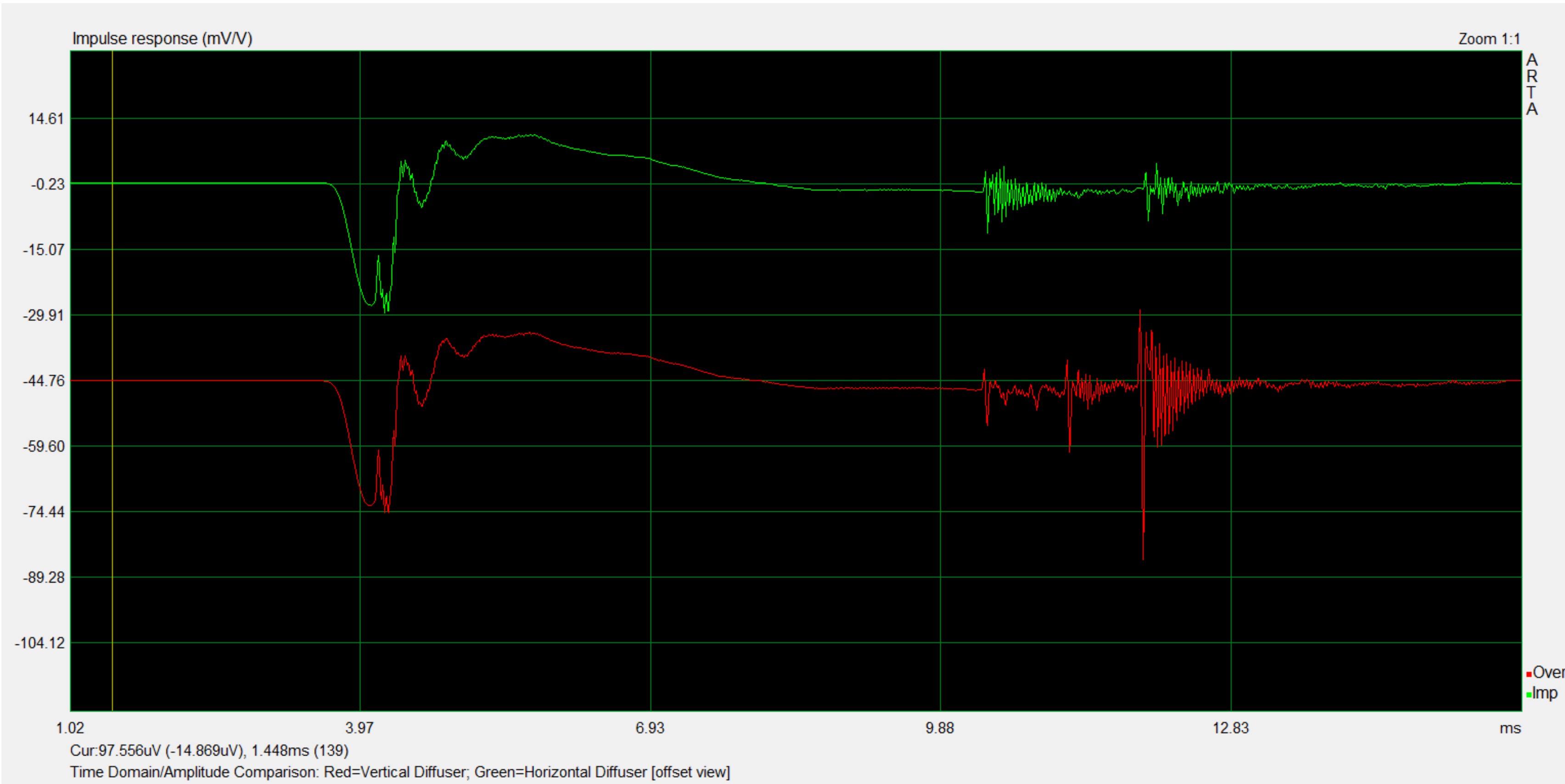

Figure 56 This diagram shows an offset overlay comparing two waveforms to each other. This prevents the confusion caused by having two traces directly on top of each other and makes time domain comparisons easier. It does however make it more difficult to make accurate amplitude comparisons.

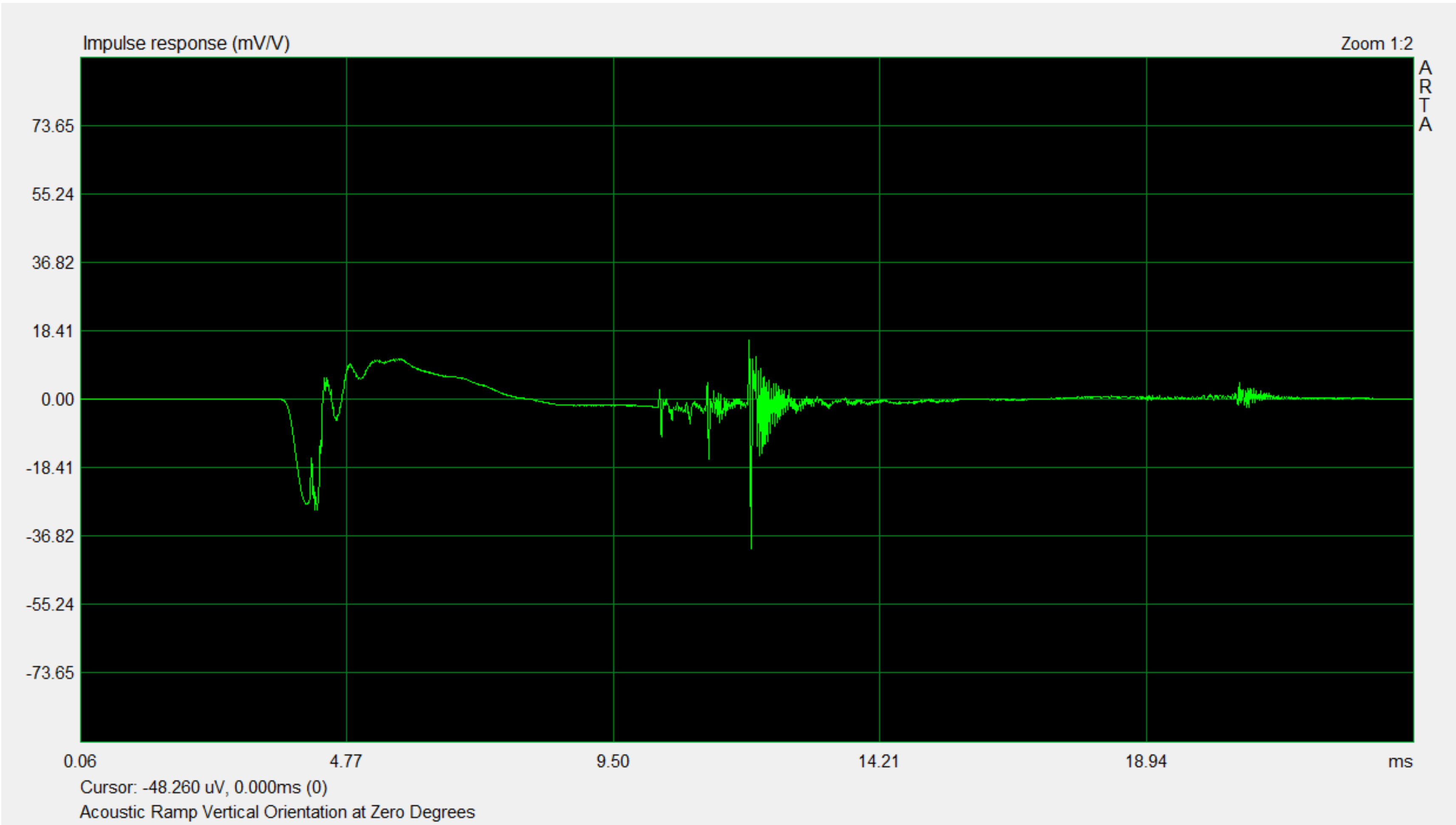

Figure 57 This waveform diagram shows how a diffusive reflection is reduced in amplitude and is spread out over time. Note the three large transients and two small transients immediately following the first.

Interpreting the Time Domain Waveforms

While a flat panel reflector creates a clearly defined and simple reflection (see Figure 54), the goal of a diffuser is to both scatter energy in many directions and over a window of time. The intensity of the reflected energy is diminished by dividing the energy of a single high-amplitude transient reflection over several transients of lesser amplitude (see Figure 57). As you can see in Figure 58 below, the reflections from the diffusers are significantly more complex in the time domain than the flat panel reflection. The white dots in the diagram depict the locations of transients.

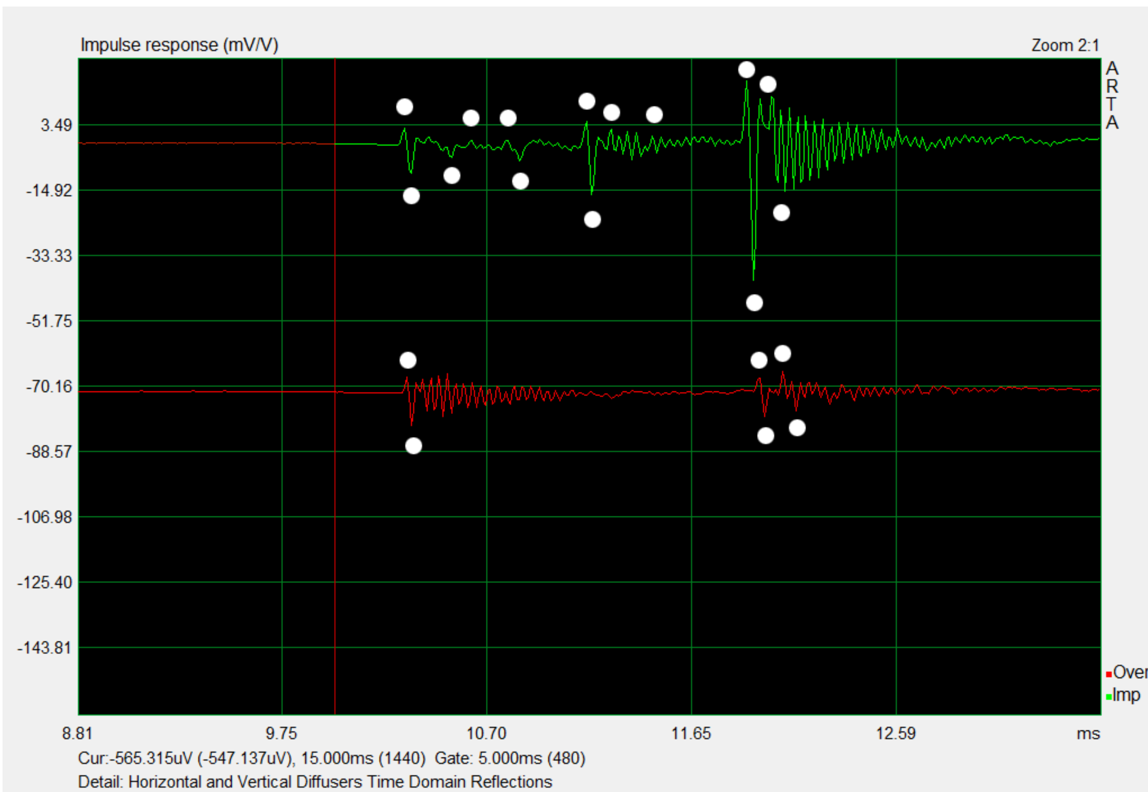

Figure 58 Waveforms for the reflections from both the horizontal (top in green) and vertical (red) reflections for 0°. White dots are used to highlight transients.

The Coefficients: Scattering and Diffusion

The two currently standardized coefficients for describing and quantizing diffusion, the scattering and diffusion coefficients, take different approaches to obtain their frequency to value pairings. Most of the scholarly materials available seem to agree that the scattering coefficient is more appropriate for use in computer models of diffusive behavior and the diffusion coefficient is more appropriate as a qualitative measure of the value of a diffuser.[10] In the Discussions section, this paper will probe the utility of these coefficients. Prior to evaluating the intrinsic value of these coefficients, the numerical data provided by the coefficients themselves must be reviewed and examined.

Below in Figure 59 to Figure 62, both the AES Diffusion Coefficient and the ISO Scattering Coefficients are plotted and compared for the flat reflector, the horizontal orientation of the diffuser and the vertical orientation of the diffuser. While both coefficients are a measure of how the diffuser performs at specific frequencies, the coefficients do not always agree. Indeed the most interesting features of the diagrams are the points where the two coefficients sharply disagree.

In the first of the comparisons, Figure 59, both coefficients do largely agree in both the contour (relative values) and quantity (actual values). The important notable properties of the flat panel coefficients are as follows:

1. For the Diffusion Coefficient, 0.2 is the value around which a flat reflector seems to hover for all frequencies(see Figure 60). The deviation from this is based on the diffraction from the edge effect.

2. Both Coefficients agree about the frequencies at which the Edge Effect is taking place
3. The Scattering Coefficient does not seem to have a single clear quantity that can be viewed as a baseline value for a flat panel, but a curved trend line is apparent (see Figure 60).

It is important to recognize what a flat panel is supposed to look like in the coefficient plots because the flat panel is the control against which the performance of the diffuser is measured when using the Normalized Diffusion Coefficient. With an extremely large reflector (approaching an infinite baffle [14]) the edge effect would be eliminated because there would be no edge to cause diffraction. This would provide the ideal control against which to evaluate the behavior of a diffuser.

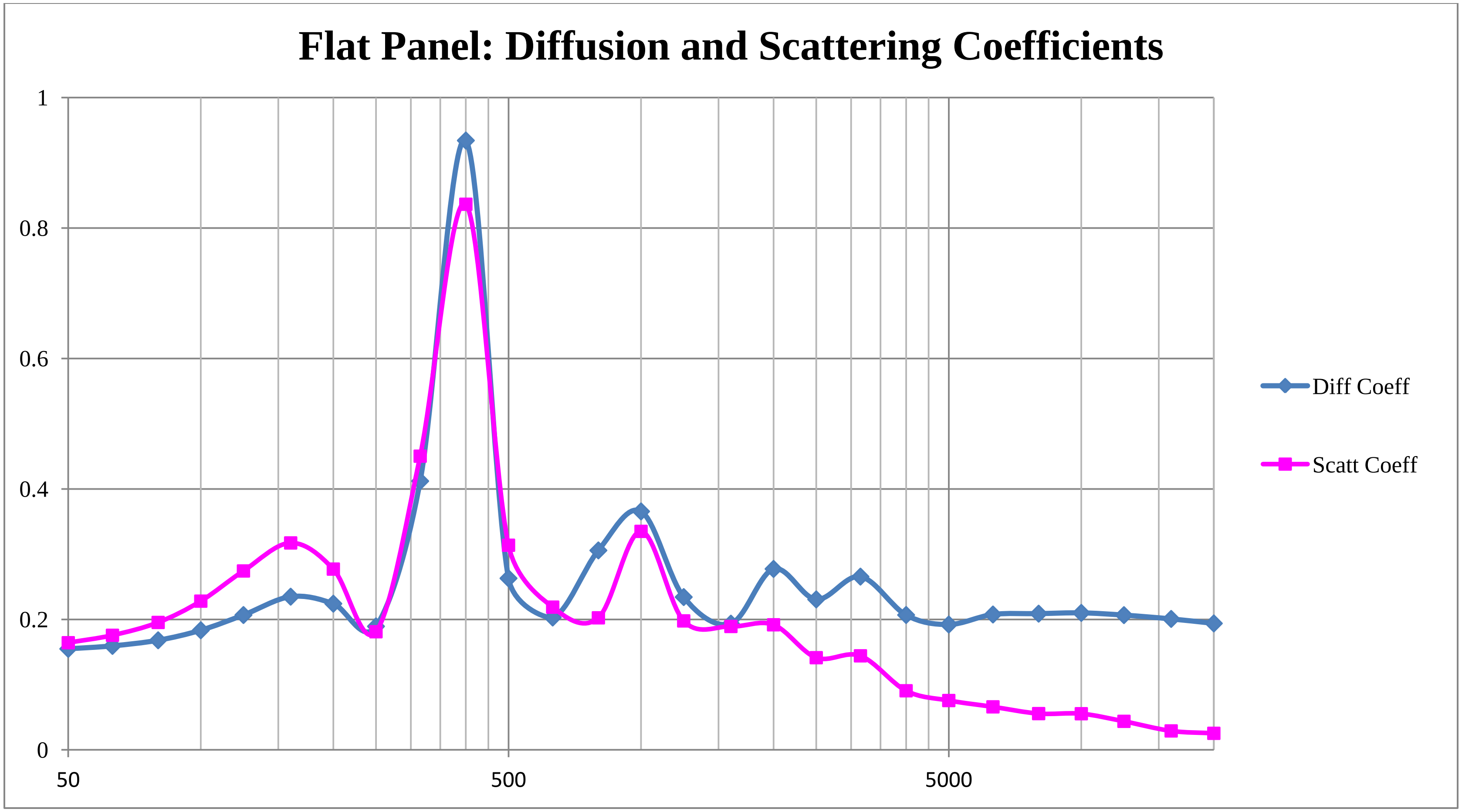

Figure 59 Comparison of AES Diffusion Coefficient and the ISO Scattering Coefficient for the flat panel

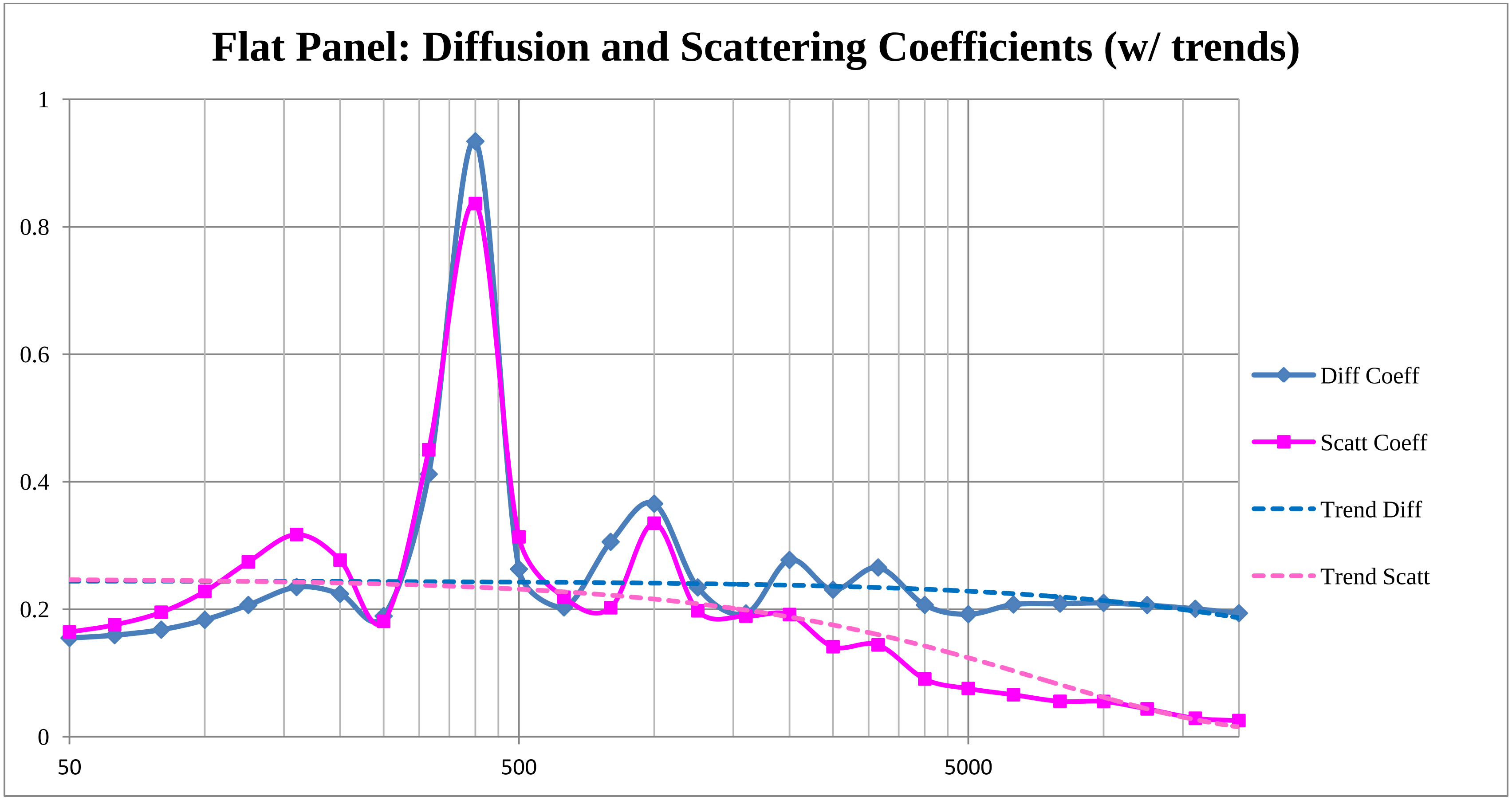

Figure 60 Adding trend lines to the previous diagram comparing the coefficients of the flat panel reflector

In Figure 61, the two coefficients clearly do not agree with each other. The curves start to diverge soon after passing the low frequency limit of error mentioned earlier, around 200 Hz - 250Hz. Neither the contours nor the quantities of the coefficients are in agreement. The specifics of these differences will be investigated in the DISCUSSIONS section, but some generalities can be inferred in this section. In both coefficients, we see the bandwidth of the effective diffusion/scattering as a general rise in the average coefficient value. Assuming for the moment that the diffuser is good at scattering, good scattering seems to be when the Scattering Coefficient is above approximately 0.7. In the case of the Diffusion Coefficient, if we again assume that the diffuser is diffusing well, the numerical coefficient range of good diffusion seems to be much lower, or above 0.4. Using both of these metrics, it appears that the effectiveness of the diffuser starts at around 250Hz and continues up through the audible range of frequencies. In both coefficients, the dotted lines represent the trend lines of each of the data ranges.

If the assumption is made that *both* the coefficients are correctly describing the performance of the diffuser, then the exercise becomes learning to interpret the coefficient numbers on their own terms. For instance, in the flat panel example, we can assume from the data that approximately a diffusion coefficient of 0.25 means that we are examining a flat non-diffusive surface.

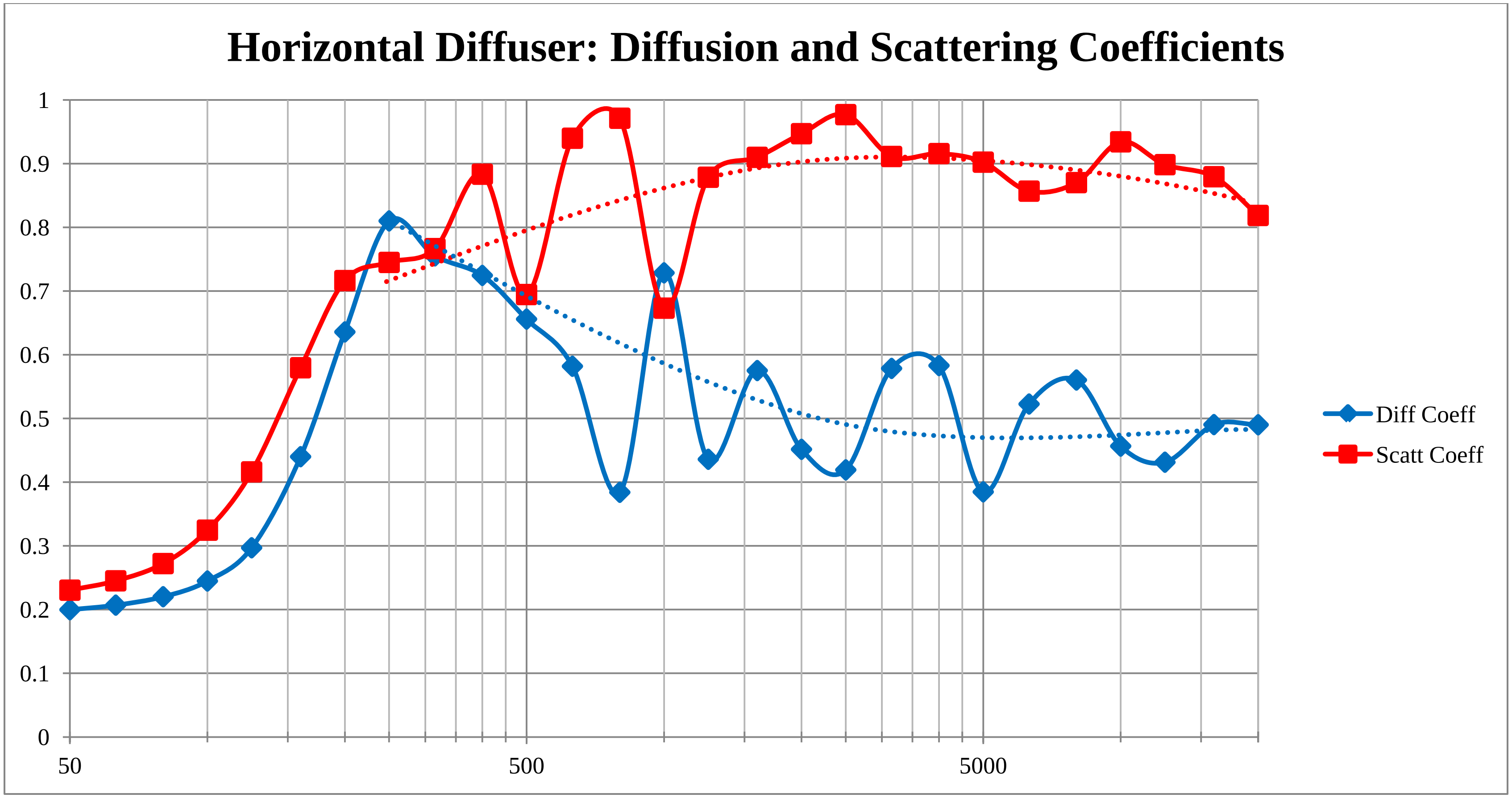

Figure 61 Comparing the AES Diffusion Coefficient to the ISO Scattering Coefficient for the horizontal orientation of the diffuser. The dotted lines represent trends for the diffusive/scattering bandwidth.

The next comparison of coefficients is in Figure 62 and the subject under test is the vertically oriented diffuser. In this case the coefficients largely *do* agree in both the contour and quantity of coefficient values. Both plots show significant dips in effectiveness at 315, 500 and 1000 Hz. This would imply flat-panel-like specular behavior for wavelengths 3.58', 2.26', 1.13' as well as their half and quarter lengths as well. With the exception of these frequencies, the diffuser seems to be effective from roughly 200 Hz to 5000 Hz.

In Figure 63 below, the normalized diffusion coefficients for two commercially available diffuser products are plotted. The QRD 734 and the Diffractal are both manufactured by RPG Inc and the data is published in the appendix of the Cox/D'Antonio book. Older coefficient data for the QRD 734 in gray is included from the marketing materials for the product for the sake of offering a complete picture. This diagram is meant to be used as a reference or a point of comparison while considering the data from the tests of the Acoustic Ramp. What should be immediately evident, is that the values of the normalized Diffusion Coefficients of the QRD 734 are quite low compared to the non-normalized Acoustic Ramp data. This is due to the fact that the normalization process tends to reduce the overall coefficient values and that the Acoustic Ramp is likely a better diffuser.

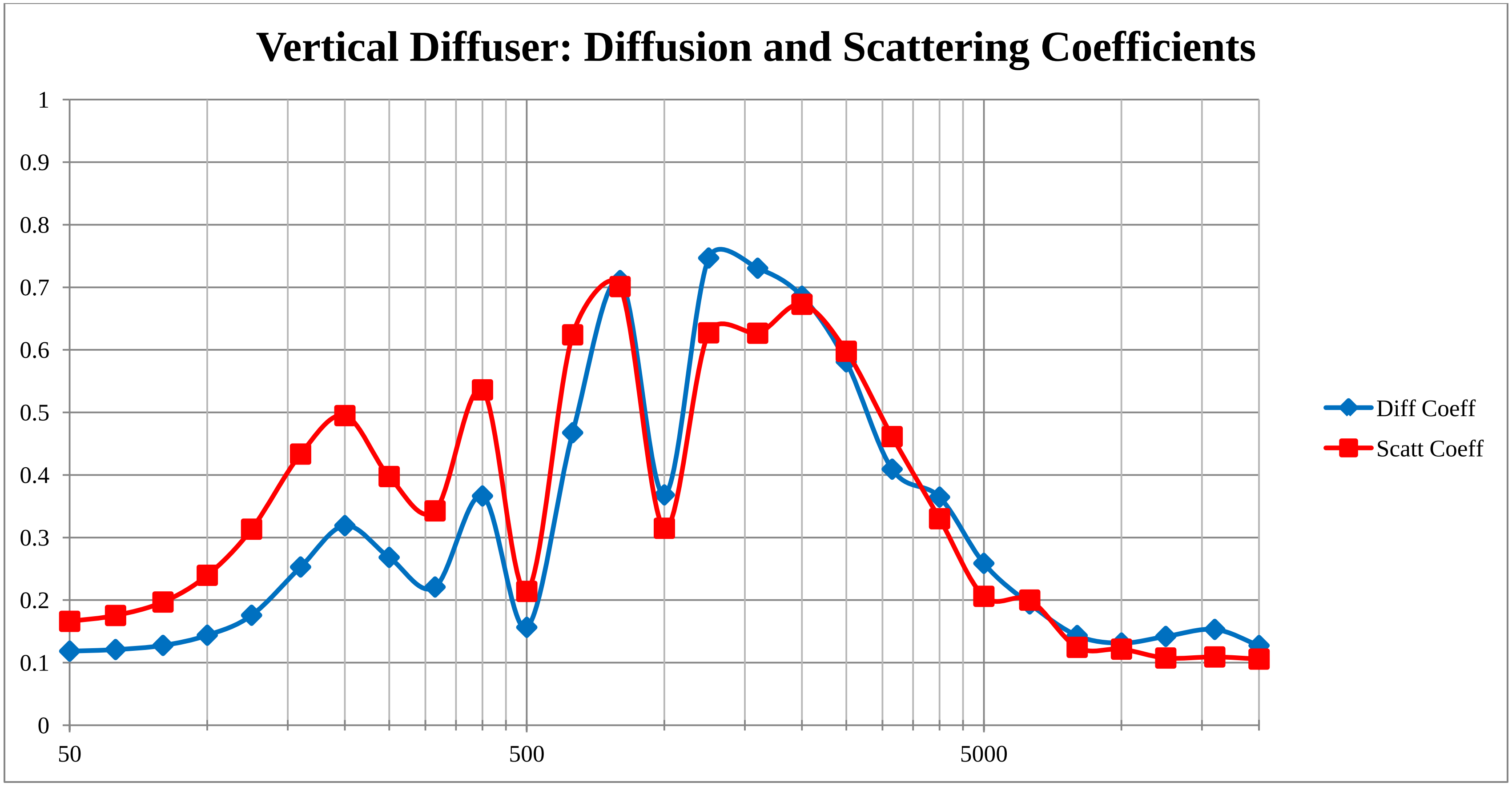

Figure 62 A comparison of the AES Diffusion Coefficient to the ISO Scattering Coefficient for the Vertical Orientation of the diffuser.

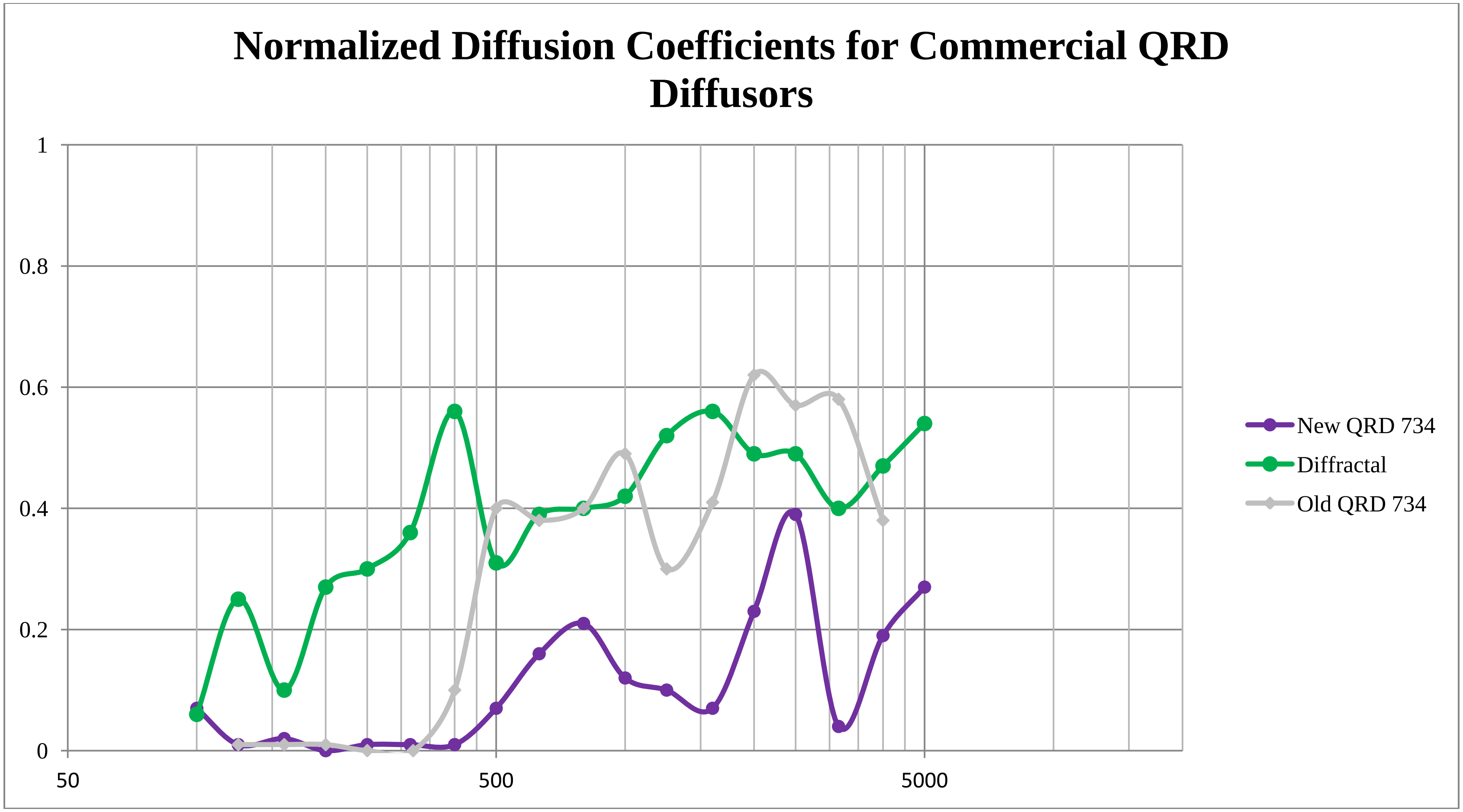

Figure 63 Published data for two commercially available diffusers: the QRD 734 and the Diffractal both manufactured by RPG Inc. [10] The "Old QRD 734" data comes from the marketing brochure for the QRD 734. [9]

DISCUSSIONS

The research and product development that has become this paper has been a continuously evolving process. Initially the paper was to be a description of the development of the Acoustic Ramp diffuser, with a hypothesis about how the diffuser would perform and why and then subsequent tests either proving or disproving the hypothesis. Although some consensus exists, the methodology for the testing of acoustic diffusers is still under healthy debate. It proved impossible to engage in the process of researching and attempting to use these testing strategies without forming opinions about the efficacy of these strategies. This added a facet to the paper in which after attempting to utilize the existing methodologies to test, collect data and evaluate the data, the methodologies themselves would be analyzed.

Schroeder was deeply aware of the problems with acoustic measurements and offers an abundance of wisdom and insight on the testing of acoustic phenomenon and the subsequent analysis of the collected data. As amusingly paraphrased by Philip Newel [19], Schroeder had lost confidence in the state-of-the-art methods of measuring and documenting reverberation in the end of the 50's and the early 60's. He was developing a new way of measuring reverb times [20] that would offer "the reduction of randomness." As time progresses, and we find new methods of evaluating data our perspectives change and evolve. The search for better measurements and metrics is part of the process of doing research.

The choice to analyze the tools of analysis is dangerous however. The very act invites criticism and requires a drop of hubris to shield the investigator from self-doubt. In order to analyze the methodology a criteria for evaluating the methodology is required. Cox and D'Antonio excellently express what a measurement of diffusion should do. Adding the process by which that measurement is obtained is a natural extension to the goals for diffuser measurement.

> An ideal diffusion coefficient (and method of obtaining said coefficient[3]) would:
>
> - Have a solid physical basis
> - Be clear in definition and concept, and related to the current and future roles of diffuse reflections in airborne acoustics, especially in rooms
> - Consistently evaluate and rank the performance of diffusers
> - Apply to all the different surfaces and geometries found in rooms
> - Be measureable by a simple process
> - Be bounded
> - Be easy to predict[10, p. 128]

Amusingly, Cox and D'Antonio liken the process of defining a good coefficient to the search for the Holy Grail. Considering all of the great minds that have been working on the diffusion and scattering coefficients for the past 20-30 years, it must be extremely difficult indeed. In a recent discussion about coefficients for measuring and evaluating diffusers[21], a group of industry-leading architectural acousticians admitted to not relying on published coefficient data in their process for specifying treatments for commercial projects. There was a consensus that published polar directivity patterns,

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[3] Parenthetically added by the author.

internal private testing and actual critical listening experience were the primary means used for evaluating diffuser performance. This seems to indicate that these acousticians have accepted neither the scattering nor the diffusion coefficients as complete means for evaluating diffuser performance. The absorption coefficient on the other hand seems to be widely accepted even though there are well known problems with the repeatability of data in various different acoustic laboratories.[10, p. 87]

The prevalence of the disuse of the diffusion and scattering coefficients brings up a question about why we have coefficients in the first place. Part of the purpose of coefficients is to make it easier to discuss, describe and think about scattering or diffusive behavior. The coefficient becomes part of the lexicon for defining the phenomenon. In addition to a single-number reduction of the captured test data, the coefficient should add additional information in order to be valuable. This brings up the question: who is the intended audience or population that will use the coefficient as a tool? While the reduction of elaborate data could be valuable to professional acousticians, it make more sense that a coefficient is much more valuable to lay people as a simple way to compare products that they intend to purchase. It is ironic that a diffuser, which is designed to increase the complexity of reflection and scattering, should be described by a coefficient that's purpose to is minimize the complexity of the captured test data.

What needs to change about the existing scattering and diffusion coefficients to allow them to be as widely accepted by the professional acoustics community as the absorption coefficient? There do seem to be some clear areas for improvement that were ascertained over the course of working with the current state-of-the-art[16] testing and evaluation methodologies. These improvements are specific to the diffusion and scattering coefficients and do not apply to the absorption coefficient which is beyond the scope of this paper. The following is a wish list for coefficient advancements:

1. Improve the process of comparison of the diffuser under test to a control flat surface. A diffuser under test may not share the same edge effect anomalies as a flat panel of the same size.
2. Improve the intuitive relationship between the appearance of a polar plot and the coefficient value. A knowledgeable acoustician should be able to guess an approximate coefficient value when shown a polar plot.
3. Devise a legend that matches coefficient values to the scattering/diffusion of known geometric objects. For instance, values between 0 - 0.2 are similar to a flat reflector, 0.3 to 0.6 are similar to a nested QRD diffuser, and 0.9 - 1.0 indicate cylinders and spheres.

Testing in the Free Field and the Problem with Flat Panels

Testing in the free field does not actually mean testing outside, suspended in mid air. Rather it is the closest approximation to this as possible. The out-of-doors is too loud and uncontrolled for accurate tests, so the tests are moved inside into the largest possible rooms available. Reflective surfaces can be avoided either with the use of anechoic absorption treatments and the time gated impulse responses. Unfortunately, both of these solutions to the problem of reflection are flawed. Even the best anechoic absorption wedges still have measureable diffraction at the front edge or apex of the wedge. [12] The room needs to be large enough to allow for a reflection-free gated time window that is longer than the length of the lowest critical frequency. A time window would need to be 1/20th of a second or 50 ms to capture a single cycle of 20 Hz. The implication is that the test facility would need to have a 56.5ft spherical radius of free space around the loudspeaker, the item under test and the test microphone in order to be accurate down to 20 Hz. Part of the free field requirement is to allow for a gated time window to avoid undesired interference from unwanted reflections, but part of it is to separate the performance of the diffuser under test from everything else.

In the real world, most people install diffusers *onto* existing walls or possibly build the diffusers *into* the walls or build diffusers *instead* of walls. The idea of testing in the free field is to isolate the diffuser from the flat wall on which the diffuser might be installed. While it might be tempting to test the diffuser in the location that it will be installed, this is not appropriate for standardized testing, only for practical testing in a specific location. The wall on which the diffuser is installed will have a specular reflection and possible diffraction and absorption as well. This acoustic response to the flat wall will interfere with and possibly mask the behavior of the reflections, diffraction and absorption of the diffuser. So the practice of testing on an infinite plane[14], while seemingly more consistent with the actual real-world utilization, can really obscure the benefits or weaknesses of the of the diffuser.

Nearly all of the proposed methods of testing and analyzing diffusion and scattering include a test of a like-sized flat panel as a control group. The idea is to control for specular reflection patterns and for the edge effect or diffraction of an object of the same size and the same distance from the loudspeaker source. The normalized diffusion coefficient subtracts the response of the flat panel from the response of the diffuser while the scattering coefficient compares the specular zone from the flat panel to the non-specular zone. The impact of the flat panel is less important in the scattering coefficient because the flat panel is providing the range of angles of the specular zone while the actual SPL values are not being subtracted from those of the diffuser's response.

Unfortunately the concept of subtracting the response of the flat panel from the response for the diffuser is a fallacy. The intended purpose of this exercise is to show how the diffuser is different from a flat panel of the same size. While this is useful information, it is not a description of the diffuser's actual behavior. The assumption is that any anomalies or errors like the edge effect or other diffraction issues will be removed by subtracting the flat panel's response. Unfortunately there is no reason to think that the edge effect/diffraction of the flat panel is the same as the edge effect/ diffraction of the diffuser. Simply rounding the edges of a flat panel changes the diffraction effects significantly, so there is very little likelihood that the response of a diffuser has anything in common with that of a similarly sized flat panel reflector. If the diffuser *was* in fact tested on the infinite plane (or a smaller approximation), and then the plane was tested without the diffuser, the effects of the plane could be subtracted from the effect of the diffuser. The plane reflector needs to be *common* to both experimental sets in order for its subtraction to be a valid method of obtaining the diffuser's actual response.

Comparing Coefficients to Polar Plots: Towards Defining a Legend

In an attempt to develop a legend explaining the physical attributes associated with coefficient values, a series of contrived directivity studies were created to generate polar plots. Taking a cue from Jakob Nielsen's card sorting techniques from his tenure at

Sun Microsystems[22], a series of cards were printed with the contrived polar plots. The goal was take these cards to a meeting with a group of architectural acousticians and ask these practitioners to sort the cards in order of their anticipated diffusion coefficient for each plot. The card sorting experiment was tried informally at a presentation of the Acoustic Ramp at Acentech in Cambridge, MA [21]. Most of the participants expressed surprise on discovering the actual calculated coefficients based on the polar plots. The coefficient needs a legend analogous to a pH color chart to aid in the interpretation of the coefficient values.

A set of charts comparing polar plots to coefficient values similar to those created for the card sorting exercise follow below with explanations about their significance.

What does a perfect diffuser look like?

A perfect polar pattern is different for the scattering coefficient and for the diffusion coefficient. Figure 64 shows a perfect diffuser which has equal SPLs for each angle of reflection while Figure 65 shows a perfect scatterer which has tiny specular reflections and perfectly equal SPLs for every non-specular reflection. This is the primary difference between the two coefficients.

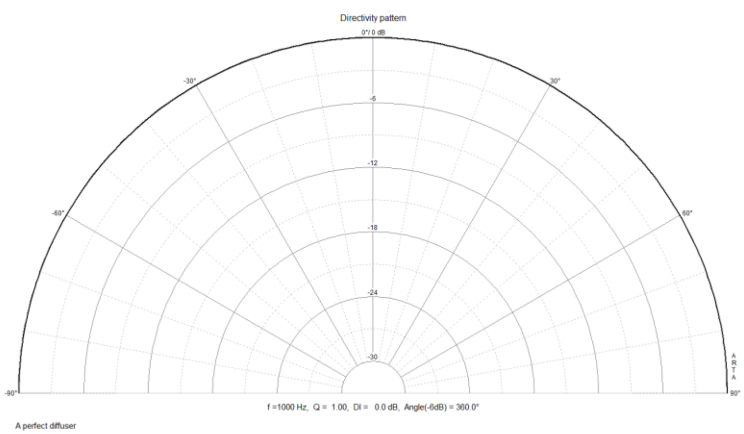

Figure 64 A perfect diffuser example where every receiver has the exact same SPL. We should of course get a d_ψ of 1 here and we do.

$$d_\psi\,(1000Hz) = 1$$

$$s_\psi\,(1000Hz) = 0.7577$$

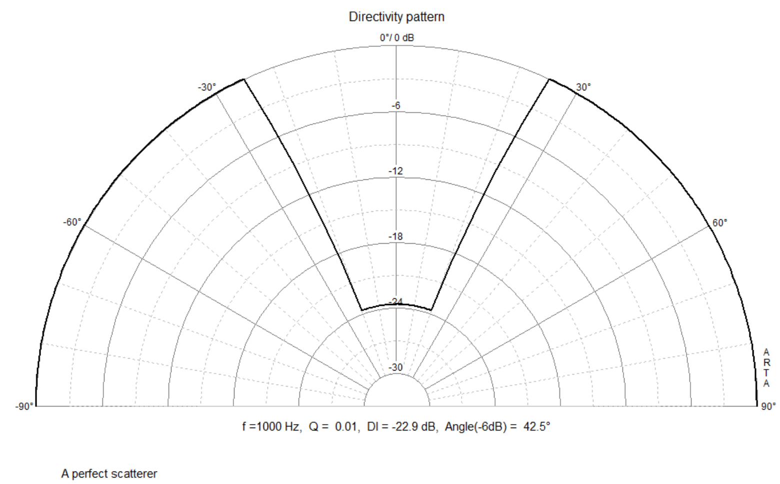

Figure 65 A near-perfect scatterer is the reverse of a specular reflection. This is similar to Feldman's "Cone of Silence" [15]

$$d_\psi\,(1000Hz) = 0.6282$$

$$s_\psi\,(1000Hz) = 0.9986$$

What does the worst diffuser (most specular reflector) look like?

Figure 66 shows a highly focused reflection at a single angle which is the worst possible diffuser, while Figure 67 shows a perfect specular reflection from +20° to -20° which yields the lowest possible scattering coefficient.

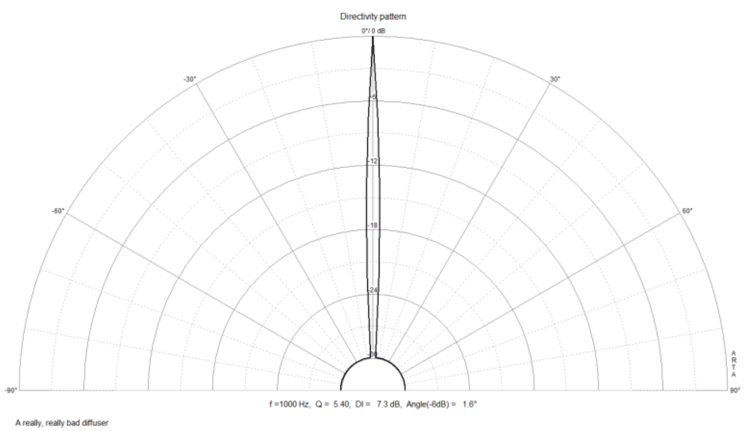

Figure 66 A really, really bad diffuser where one receiver has a very high SPL and the rest have low SPLs. We would expect a very low d_{ψ} and very low s_{ψ} and we get it.

$$d_{\psi}\,(1000Hz) = \;0.0003$$

$$s_{\psi}\,(1000Hz) = \;0.0048$$

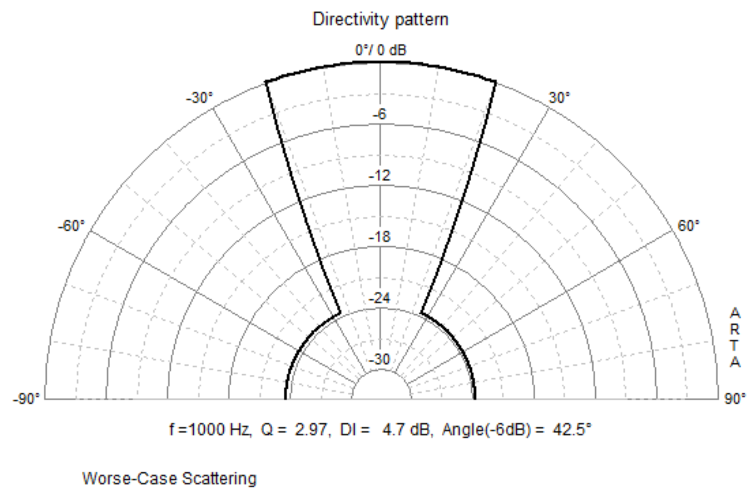

Figure 67 A worst-case scatterer: a specular reflection from +20° to -20°.

$$d_{\psi}\,(1000Hz) = \;0.339$$

$$s_{\psi}\,(1000Hz) = \;0.013$$

The effect of shallow and deep lobing

Shallow lobing like the 3dB difference in Figure 68 or 12dB in Figure 69 has very little effect on the scattering coefficient as compared to the equal power reflections in Figure 64. It does has a very strong effect on the diffusion coefficient cutting the value nearly in half.

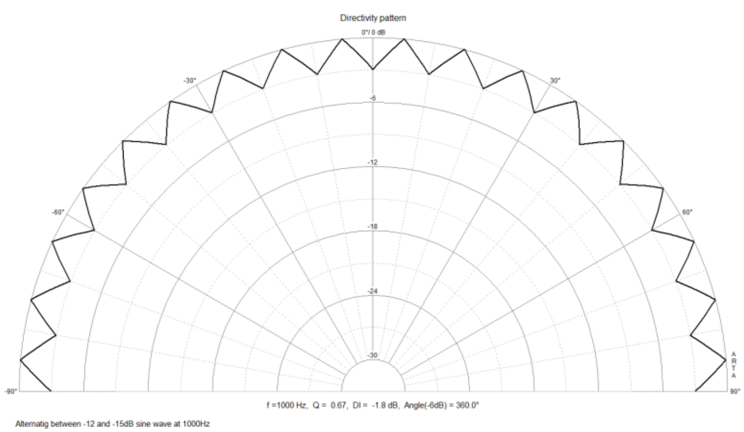

Figure 68 This polar distribution was created by alternating between -12dB and -15dB sine wave samples and represents an interesting example of diffusion coefficient math.

$$d_\psi\,(1000Hz) = \;0.8941$$

$$s_\psi\,(1000Hz) = \;0.7636$$

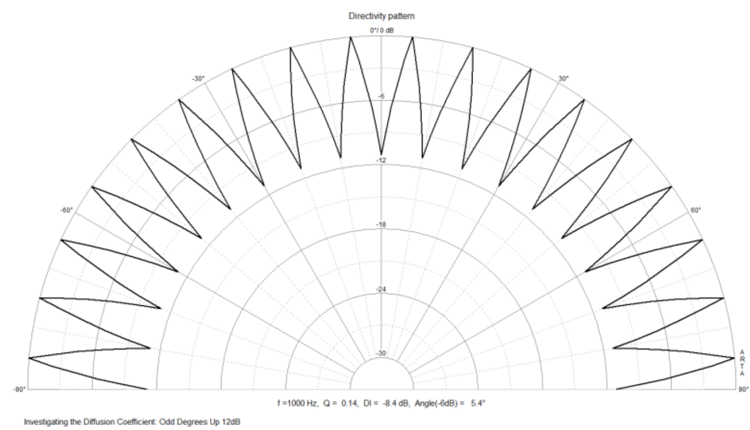

Figure 69 This polar distribution was created by alternating between -12dB and -24dB pink noise samples. There are 18 receiver positions at -12dB and 19 at -24dB.

$$d_\psi\,(1000Hz) = \;0.5418$$

$$s_\psi\,(1000Hz) = \;0.7747$$

Changing the orientation of reflected energy

In Figure 70, Figure 71 and Figure 72, the lobing pattern of the previous example (Figure 69) is re-arranged so that all 18 louder SPL's are grouped together and all the 20 quieter are similarly grouped. The first example looks like a wide specular reflection, the second rotates the center of the energy to ±45° and the third moves the energy to the extremes centered on ±70°.

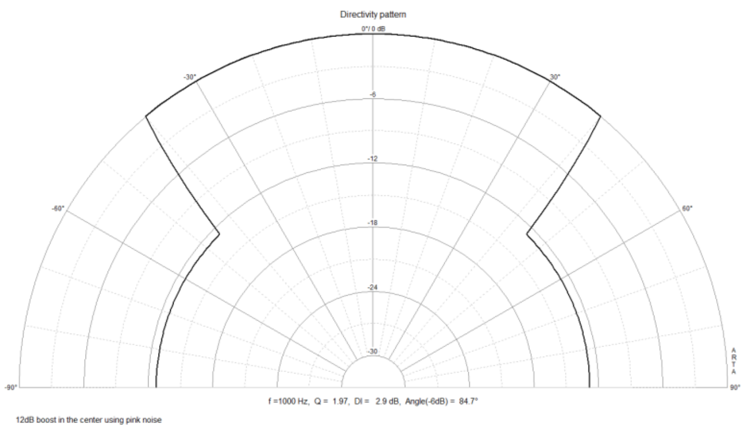

Figure 70 In this example there are 10 receiver positions at -12dB and 19 at -24dB, but the center of the polar distribution is up 12dB instead of alternating.

$$d_{\psi}(1000Hz) = 0.701$$

$$s_{\psi}(1000Hz) = 0.5013$$

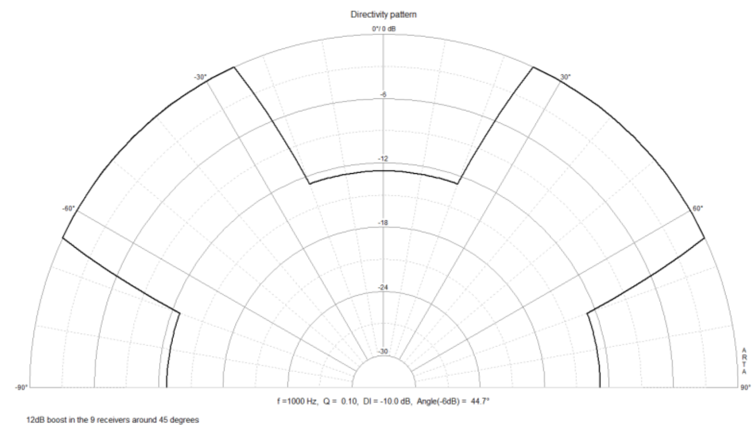

Figure 71 In this example that are again 18 receiver positions at -12dB and 19at -24dB, but this time the boost is centered around 45 degrees.

$$d_{\psi}(1000Hz) = 0.6638$$

$$s_{\psi}(1000Hz) = 0.9752$$

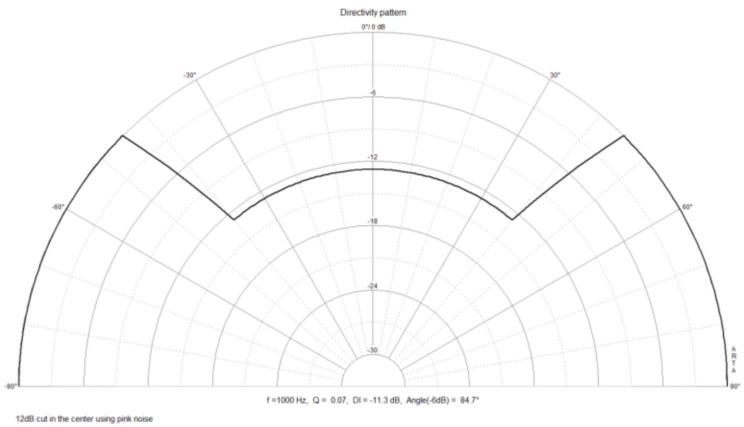

Figure 72 In this example the loud reflections are rotated to the extreme angles and the center of the polar distribution is 12dB lower.

$$d_{\psi}\,(1000Hz) = \; 0.3676$$

$$s_{\psi}\,(1000Hz) = \; 0.9744$$

What's clear from this group of three examples is that the scattering coefficient gets a high value as long as the specular zone is quiet, but it does not care how widely the energy is reflected. The diffusion coefficient wants the specular zone to have energy equal to the non-specular zone and it prefers having the bulk of the energy as close to centered around 0° as possible. The diffusion coefficient gives very high marks to the nearly specular reflection in Figure 70, slightly less to the 45° version in Figure 71, but marked lower scores for the reflection to be pushed to the extreme angles.

How specular is specular?

The next five polar plots experiment with louder and quieter centered reflections to see how boosting or cutting the ±10° region affects the two coefficients. Even a 3dB boost in the center of the plot knocks nearly 35% off of the scattering coefficient, but only reduces the diffusion coefficient by around 10%. As the boost gets more extreme, both coefficients start to agree more about the results. Attenuation of the center however is not as sensitive to either coefficient for small or large changes.

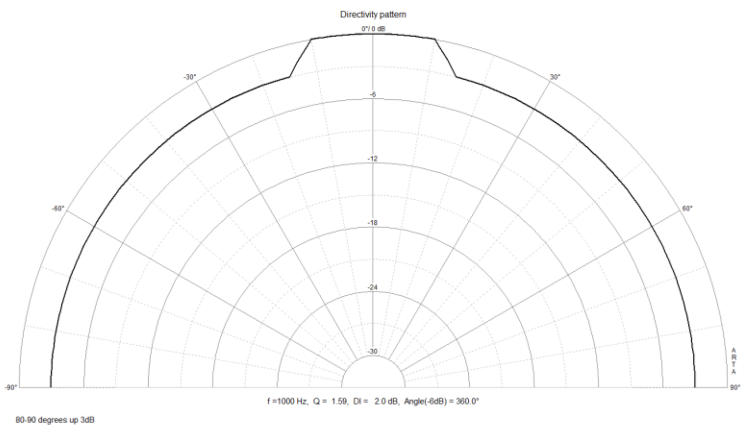

Figure 73 This polar distribution was created with +3dB from 80 - 90 degrees.

$$d_{\psi}(1000Hz) = 0.8966$$

$$s_{\psi}(1000Hz) = 0.667$$

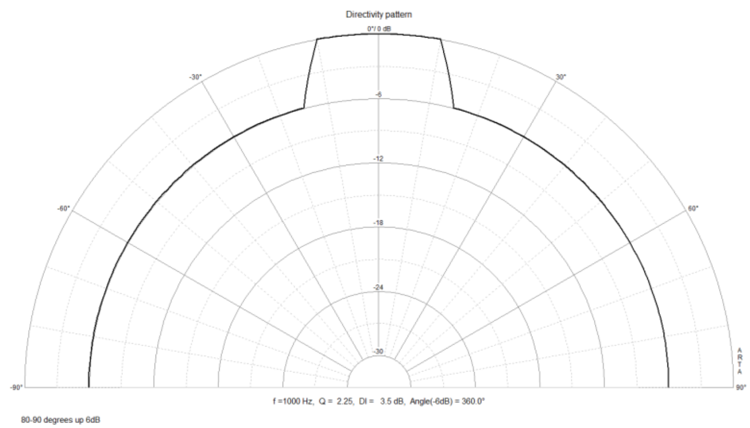

Figure 74 This polar distribution was created with +6dB from 80 - 90 degrees.

$$d_{\psi}(1000Hz) = 0.6269$$

$$s_{\psi}(1000Hz) = 0.5394$$

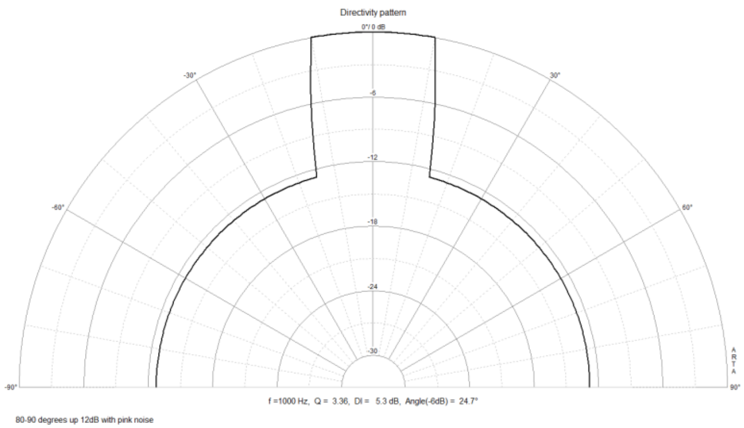

Figure 75 This polar distribution was created with +12dB samples at 80 - 90 degrees.

$$d_{\psi}\,(1000Hz) = \;0.2598$$

$$s_{\psi}\,(1000Hz) = \;0.2196$$

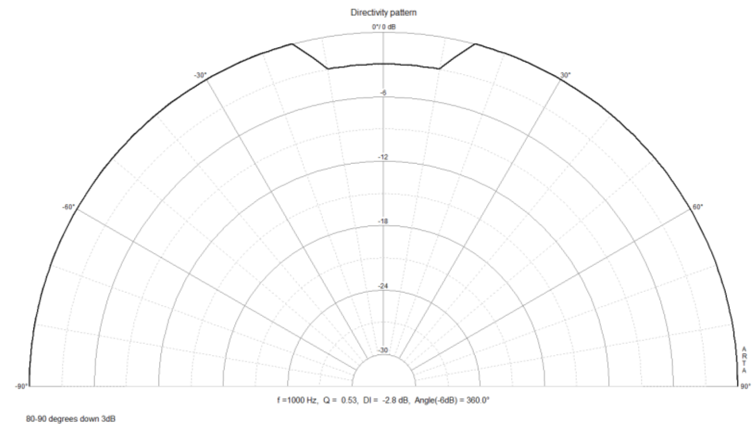

Figure 76 This polar distribution was created with -3dB from 80 - 90 degrees.

$$d_{\psi}\,(1000Hz) = \;0.9512$$

$$s_{\psi}\,(1000Hz) = \;0.8115$$

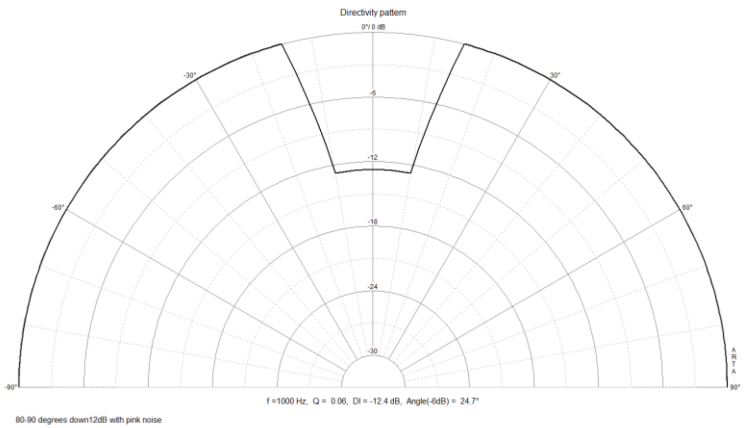

Figure 77 This polar distribution was created with -12dB samples at 80 - 90 degrees.

$$d_{\psi}\,(1000Hz) = \ 0.813$$

$$s_{\psi}\,(1000Hz) = \ 0.8679$$

What can we conclude from these example polar distributions and associated diffusion coefficients? The temptation is to judge that one or both coefficients are deficient at correctly summarizing or abstracting certain types of polar patterns. In fact, both of the numbers are merely manipulations of the given data. Neither coefficient *understands* the concept of diffusion. Both are essentially fancy averages. The major difference between the two is the inclusion of the importance of the specular zone in the scattering coefficient. This is both an advantage and a disadvantage. A wedge-shape or pyramid would rank highly with the scattering coefficient when in reality the specular reflection is merely moving to a different angle. In this case, the diffusion coefficient would probably offer a more honest valuation of the shape as a diffuser. The absence of a specular reflection is not necessarily a good thing. A sound reflected away from the listener may as well have been absorbed. Although perception is beyond the scope of this paper, suffice to say that some specular reflection is important feedback for listeners and performers alike. This has no impact on the value of the coefficients themselves, but rather on how they are used.

There is a risk in using and relying upon coefficients to value the quality or the behavior of diffusers. Details are obscured. The subtleties of the coefficients are not obvious without serious study and comparison. The examples of the rotating specular reflection shows one of the major weaknesses of both the scattering and diffusion coefficients. The absence or presence of centered specular reflections is another major weakness, where the coefficients' value might be surprising based on the polar distribution. If coefficients are intended to be used to help trained acousticians describe and evaluate diffuser performance, then they are unsatisfactory. A trained professional can gain much more insight into a diffuser by looking at a sonogram or at series of polar responses. If the goal of the coefficients is to make it easier to sell acoustic treatments to end users, then the coefficients both have weaknesses in describing certain shapes. A customer would be wrong to assume that a diffuser with a diffusion coefficient of 0.5 at 800 Hz is actually better than a diffuser with a 0.4 at 800 Hz. There is more work to do in defining a good coefficient to describe diffusion.

What Do We Want a Diffusion Coefficient to Do?

If the goal of developing a diffusion coefficient is to have a metric for showing that one diffuser is better than another, then first the definition for a perfect diffuser must be agreed upon. If, for the sake of argument, it is assumed that the definition of a perfect diffuser is a shape that equally distributes reflected energy over all directions in a semi-circular or hemispherical pattern then an excellent qualitative diffusion coefficient will need to do the following:

1. Value the even distribution of energy as better than uneven distribution
2. Value lower variance from the mean SPL value as better than higher variance from the mean.
3. Value larger number of hot spots or lobes as better than smaller number of hot spots or lobes.
4. Value widely spaced hot spots or lobes as better than closely spaced hot spots or lobes.

Is there an existing formula or process that will yield the above valuation of SPL directivity data? One process for finding a formula might be to rank a large set of polar plots by knowledgeable acoustics. Then existing statistical formulas would be run on the data attempting to find a method that matches the ranking by the experts. While there is probably a more mathematically sound manner in which to do this, this author suspects that it will still work.

CONCLUSIONS

What started out as the creation and evaluation of a novel acoustic diffuser has become a critique of the existing methodology from the measurement and analysis for diffusion and scattering. Returning to the original mission, how well does the Acoustic Ramp work? In short, the Acoustic Ramp diffuser works very well. Based on testing, it is evident that the treatment is effective both as a scattering device and as a diffusing device. Due to the fact that the Ramp works in more than one dimension, it creates significantly more complex reflections, changes in orientation and alterations of time and phase than standard 1D diffusers of similar size. While it was expected that the angled reflectors at the rear of the wells would yield specular reflections at specific angles (see Interpreting the Horizontal Orientation Sonograms and Figure 23) they did not. Scattering occurred on much wider angles of reflection, without a clear pattern. The expected specular zone is largely empty of reflected energy which yields excellent values for the Scattering Coefficient.

The Ramp does seem to loosely follow Schroeder's diffuser math for bandwidth in the vertical orientation, though there are several frequencies ranges that remain specular even within the expected functional bandwidth of diffusion. The sonogram plots for the vertical orientation are much less dramatic than those for the horizontal orientation because the energy is directed by the wedge shape away from the test microphones. The free field testing does seem to indicate the diffuser works very well. It is anticipated that it will perform very well in actual rooms also.

The next exercise, the evaluation of the current methodology for testing, measuring and evaluating diffusers, had a much more mixed outcome. The creation of sonogram and polar plots are extremely useful. It is easy to see how energy is reflected and distributed in the frequency and amplitude domains. The time domain seems to be more difficult to analyze and there is much work to do in visualizing phase and time against directivity. The reduction of the data into coefficients is another matter.

While the ISO Scattering Coefficient and Diffusion/Normalized Diffusion Coefficients do seem to provide some meaningful insight, their coefficient values are often surprising and lack an intuitive relationship with the polar responses from where they are derived. The Scattering Coefficient is a good measure for comparing a specular reflector to a diffuser/scatterer but it is critical that coefficient is not used as a metric describing the merit of the device. The Scattering Coefficient views perfection as the "cone of silence" depicted in Figure 65.

The Diffusion Coefficient seems to be more problematic. A legend similar to a pH color chart is required to help interpret the numeric values. There is not a linear relationship between the diffusion coefficient and the intrinsic value or merit of a diffuser. Further, the notion of the Normalized Diffusion Coefficient, where the response of the flat panel is subtracted from the response of the diffuser is flawed. It would seem that while the comparison of the directivity data of a flat panel to that of a diffuser may be interesting, it is not a valid way of isolating the performance of the diffuser. There is no reason to assume that a diffuser and a flat panel of the same size would share the same acoustic anomalies from the edge effect or other diffraction.

Due to the problems mentioned here, it is the recommendation of this paper that evaluations and analysis of diffusion and scattering be done with the actual measured directivity data and the sonograms and polar plots derived from that data.

RECOMMENDATIONS

Now, having completed the first phase of testing for the Acoustic Ramp diffuser and having had an opportunity to use the current testing methodologies, several additional research directions have been exposed. Although the analysis of the Scattering and Diffusion Coefficients did not yield positive results, the raw data and the sonogram visualizations of the data have proved to be extremely valuable in examining the scattering and diffusive behavior of the diffuser. Ultimately, although the coefficients are tempting as time-saving and simplifying tools, they are more useful for the layperson or the consumer and not the expert.

There exists very little research that seeks to predict the edge effects for flat panels. There were many articles that explained the general concept of what was happening in an aperture of an infinite baffle or with a series of like sized panel, but nothing with frequency specific predictive formulas. If it turns out that subtracting the response of a flat panel of like size *is* the correct way to evaluate a diffuser, then understanding the edge effects on panels is essential.

This paper sought to understand the physics of the acoustic behavior of the acoustic ramp, but neglected the perceptual effects. A great deal of listening would be required in many different setting to fully understand how the Acoustic Ramp affects the perception of music, spatial localization, timbre and perceived volume of rooms. A good starting point would be to compare a vertically oriented array of diffusers to a horizontally oriented array of diffusers in the rear of a control room or critical listening lab.

The Acoustic Ramp is a rather complex shape that scatters and diffuses sound with somewhat unexpected and surprising results. It would be very interesting to approach the analysis of poly-cylindrical and hemispherical diffuser which are significantly simpler shapes in a similar manner. Of particular interest is the lack of time and phase changes inherent to a poly-cylindrical diffuser, making for a simpler reflected wave-front which should be easier to analyze. A hemi-conical shape with a large diameter tapering to a small diameter is another enticing subject for diffusion research.

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