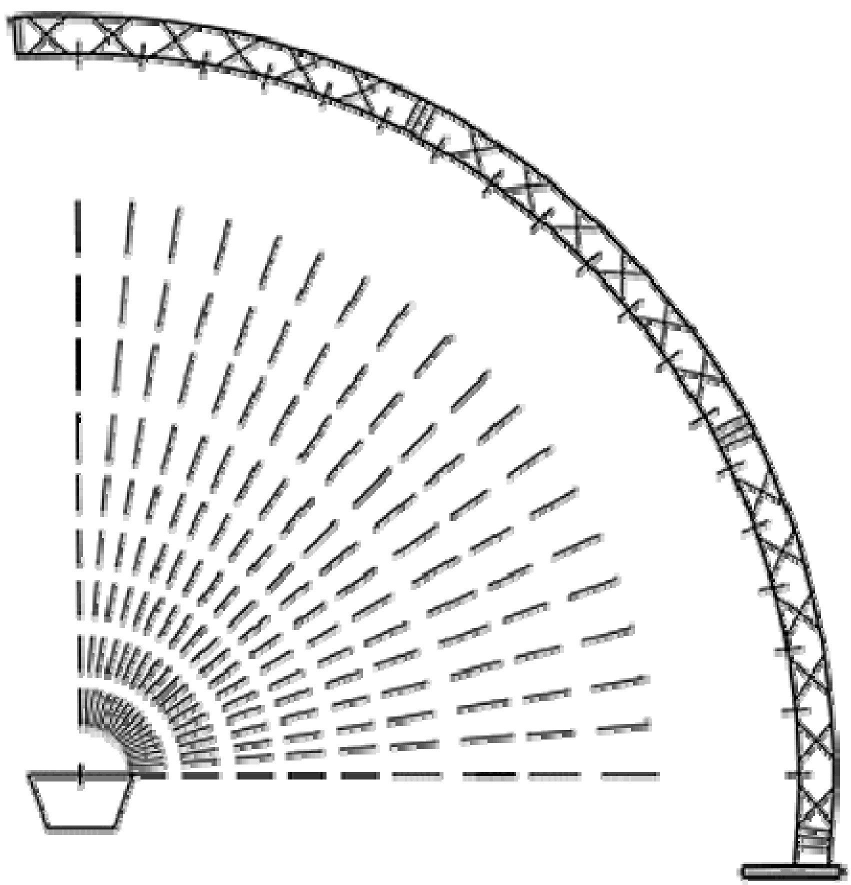
How Accurate is Your Directivity Data?

A white paper detailing an idea from Ron Sauro:
A new method and measurement facility for high speed, complex data acquisition of full directivity balloons



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How Accurate is Your Directivity Data?

Stefan Feistel and Wolfgang Ahnert have shown in their paper "The Significance of Phase Data for the Acoustic Prediction of Combinations of Sound Sources" presented at the 119th AES Convention, that the use of complex data yields much more accurate predictive models of acoustical performance than do models using magnitude only data. This increase in accuracy is significant; between 1 and 2 orders of magnitude depending on other variables. For certain conditions, previous models could be of questionable validity above their defined "critical frequency" when using magnitude only data. The critical frequency is a function of the distance of the acoustical sources from the actual point of rotation when measured.[1] The question would now seem to become how one gets accurate complex data for use in predictive modeling.

Introduction

The task of acquiring accurate complex data on sound sources (namely loudspeakers) is not a trivial one, but it is possible. Several items must be considered prior to embarking on this task.

1. What are the band limits of interest?
2. How large is the loudspeaker?
3. How far away from the loudspeaker must the measurement mic be located?
4. How accurately must the measurement mic be positioned?
5. Is the measurement environment time-invariant (stable)?

We need to place some size limits on the measurement environment and subsequently on the loudspeakers to be measured. With this in mind we will confine ourselves to radiation elements with a maximum dimension of 39 inches (1.0 m) for frequencies less than 1 kHz. At 10 kHz the maximum dimension can not exceed 16.5 inches (0.42 m). With these size limitations we can measure the far field performance of the loudspeaker at a distance of 4 m with reasonable accuracy.[2, 3]

However, when multiple radiation elements are used within the same frequency region there is an additional criterion that must be considered. For this case the far field is a function of the spacing between the radiators. As a loudspeaker is rotated, the spaced radiators will change their relative distance when observed from an off-axis location. This will cause a level change of each radiator with respect to the other(s) as observed at an off-axis microphone location. The worst case will occur at 90° off-axis. In the true far field (infinity), the level difference (error) will be zero. At finite distances the level error will increase with decreasing measurement distance. In order to keep the level error between sources of identical output to less than 1.0 dB at all radiation angles the spacing of the sources should not exceed 19 inches (0.48 m) when measuring at a distance of 4 m.

This same principle is applicable to enclosure edge diffraction. However, as the amplitude of the diffraction is not identical to the original source that illuminated the diffractive edge, the same criteria for spacing cited above may not be applicable.[4] This will be addressed in future work.

We will take our bandwidth of interest as 100 Hz - 10 kHz as is standard for most acoustical modeling software. The accuracy of the microphone position will be directly related to the high frequency bandwidth limit and the desired accuracy of the complex (phase) data to be measured. If we allow a maximum error of $\lambda/8$ (45°) our mic must be within 0.17 inches (4.3 mm) of its intended position.

The stability of the measurement environment is by far the greatest challenge. The measurement environment must remain time-invariant during the measurements for them to be accurate. Typically, to capture the full directivity balloon will require approximately 2,600 individual impulse response (IR) measurements for an angular resolution of 5°. Each one of the individual IR measurements may take as much as 10 or even 15 seconds when test time and loudspeaker rotation are considered. If everything goes perfectly during the test it will take from 7 - 11 hours to complete.

Temperature can be one of the most difficult items to control over this extended period. Of course if the measurement time could be reduced it would be easier to conform to the time-invariant constraint.

A New Method

Taming Temperature Variations

The number of individual measurements required is the primary reason for the extended measurement period for full directivity balloon data acquisition. A method for greatly reducing the total time required is to use multiple microphones at the appropriate positions. By using 19 response-matched microphones spaced at 5° intervals from 0° (straight up / vertical) to 90° (lateral / horizontal) the full directivity balloon can be measured in approximately 30 minutes. The loudspeaker to be measured is placed face up firing at the 0° microphone and the front hemisphere of the directivity balloon is measured. The loudspeaker is then flipped over so that it is firing straight down. The rear hemisphere of the directivity balloon is then measured.

The signals from the microphones are fed through high quality microphone pre-amps and analog-to-digital converters. The digital data streams are then sent to a PC running EASERA[5] which can easily capture and process all of them simultaneously.

These microphones are held rigidly in position by a 100° arc of a curved aluminum truss with an interior radius of 4.4 m (Figure 1). The truss is treated with broadband absorption to greatly attenuate any reflections that may occur from the cylindrical aluminum. The microphone diaphragms are also spaced sufficiently forward of the truss so that reflections from the truss are not an issue (Photo 1).

This microphone array is located in a large anechoic chamber which is built into the side of a large hill (Photo 2). The majority of the chamber is below grade. The combination of the greatly reduced measurement time and the large thermal mass, encapsulating over

75% of the chamber, greatly aids in satisfying the time-invariant constraint relating to temperature during the course of a full balloon measurement.

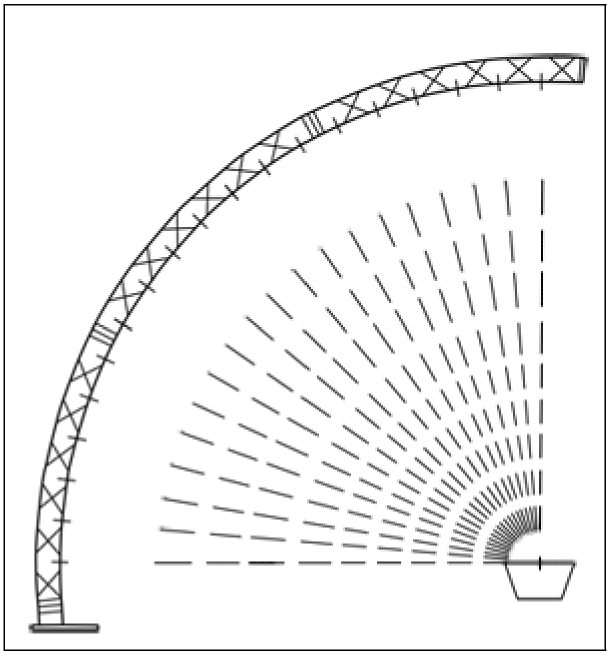

Figure 1 – Microphone array and loudspeaker location (not to scale)

Accurate Loudspeaker Positioning

The angular positioning of the microphones in the array is very accurate. They are placed using precision machined parts at precise locations in the truss. The axes of the mics located at 0° and 90° (as well as all the mics between these two positions) intersect at a single point in space. It is this point around which the loudspeaker must be rotated to obtain accurate directivity data, complex or otherwise. A simple, yet elegant, yoke apparatus was designed and fabricated to accomplish the task of holding the loudspeaker in the proper position while allowing for rotation about the correct point.

The point of rotation (POR) for the turntable/yoke has to be positioned coincident with the microphones axes. A five-way laser was used to accomplish this. The turntable and yoke were leveled individually. The five-way laser was placed in the yoke centered with the point of rotation. For the turntable/yoke this point is defined by the turntable's axis of rotation and the yoke's axis of rotation. These two axes are orthogonal and define the point of rotation. The turntable was then moved into position so that the five-way laser illuminated the reference targets (90° mic, 0° mic, turntable rotation point and the center of the left & right yoke verticals) simultaneously (Photo 3-Photo 5).

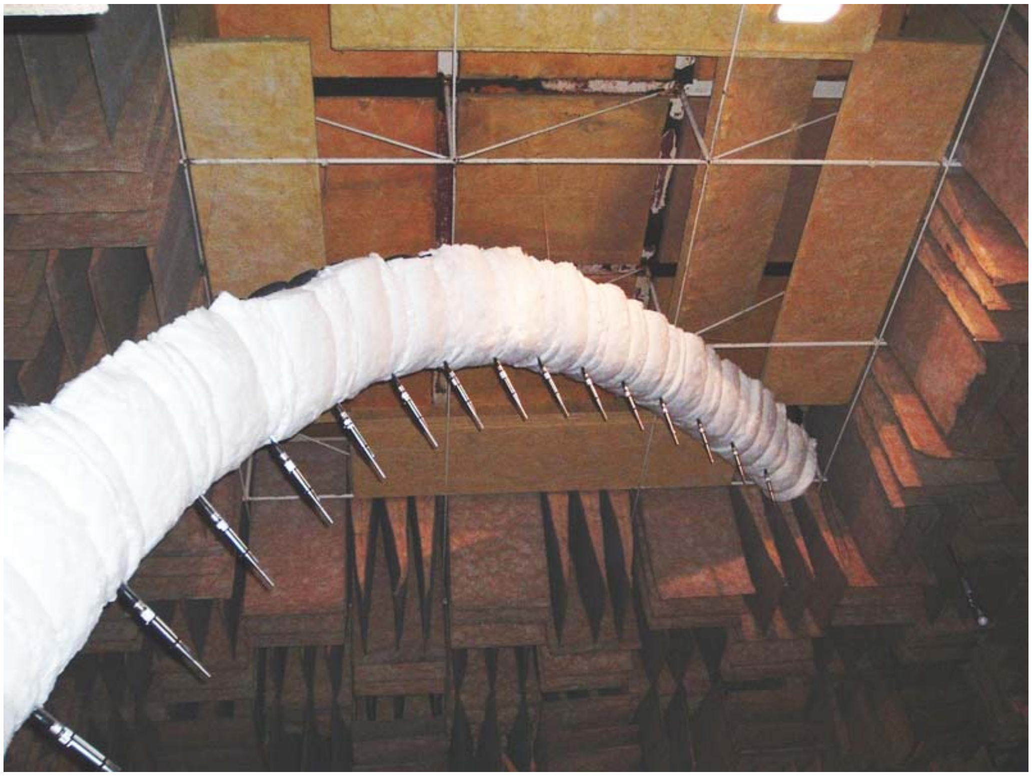

Photo 1 – Upper section of finished microphone array

Photo 2 – Exterior of the building in which the anechoic chamber is located

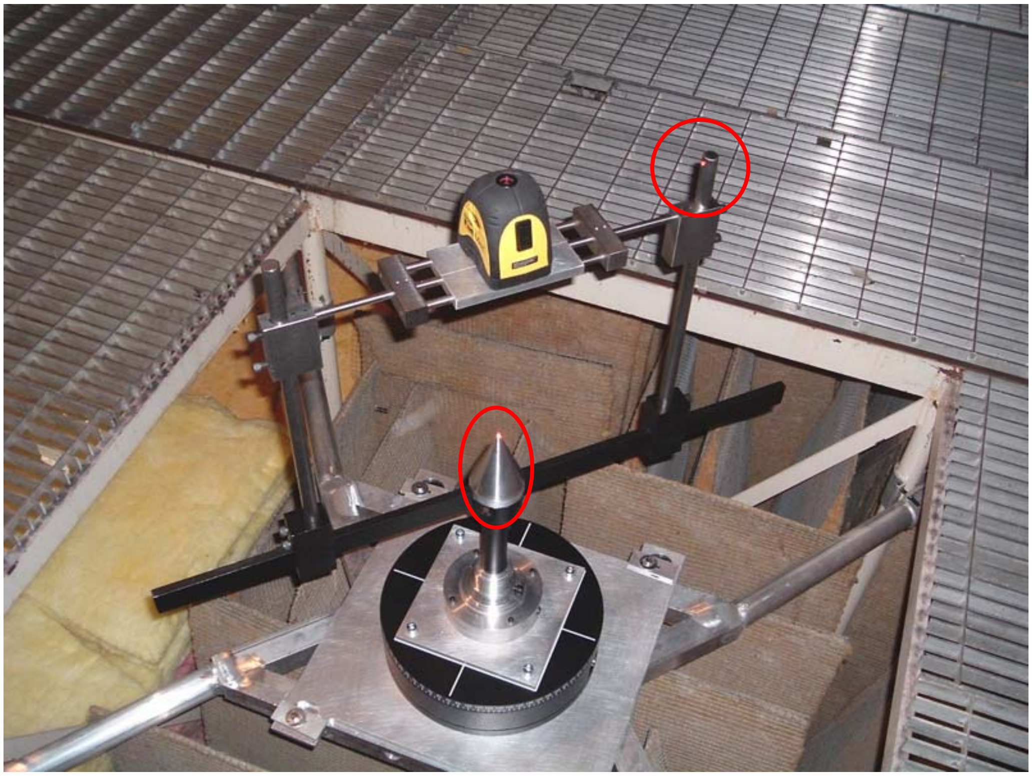

Photo 3 – Alignment of five-way laser in turntable/yoke (Note laser beam in circled areas)

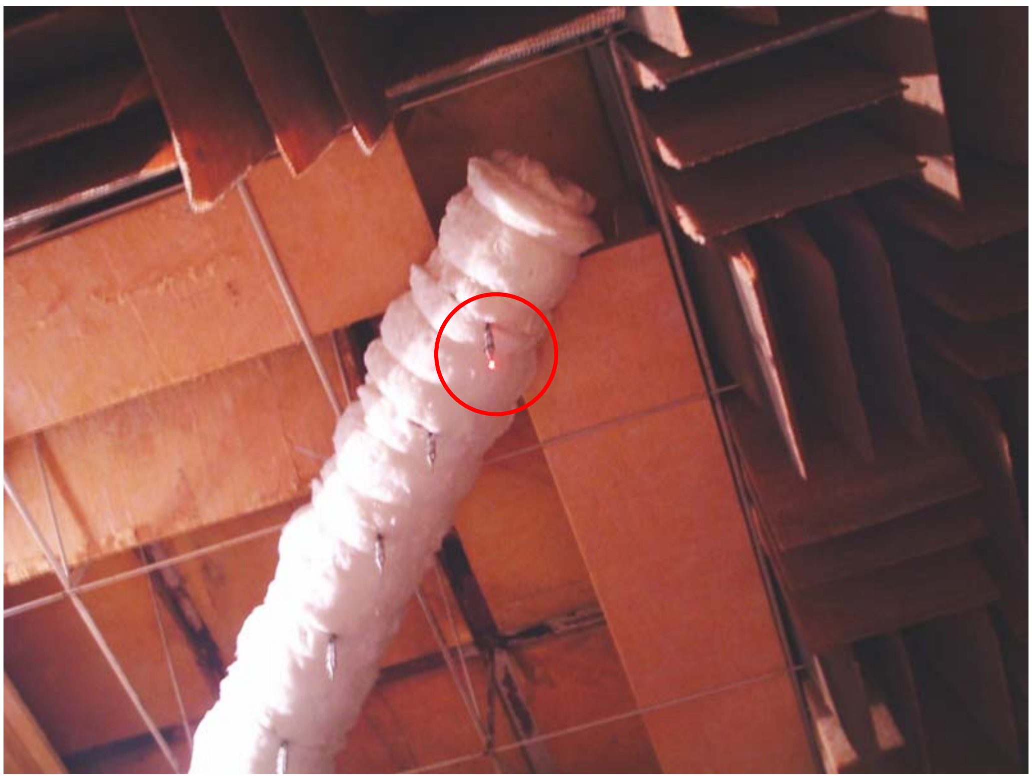

Photo 4 – Alignment of turntable/yoke to 0° mic (Note laser beam in circled area)

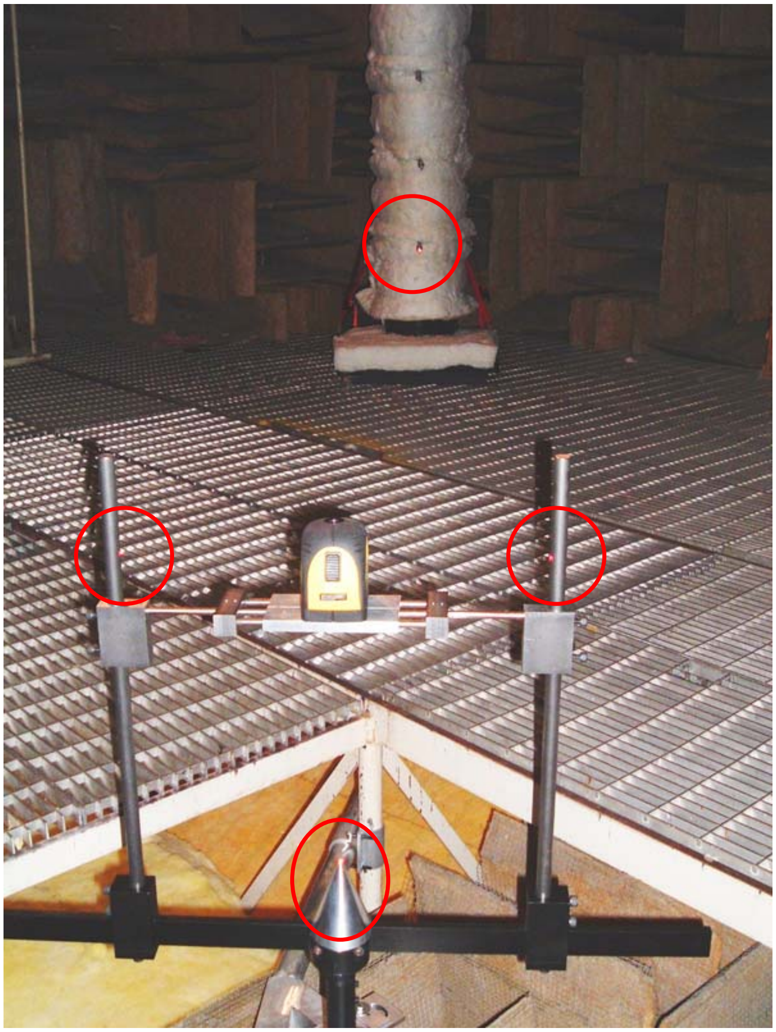

Photo 5 – Alignment of turntable/yoke to 90° mic (Note laser beam in circled areas)

Taming the Chamber

During the course of setting up and calibrating the measurement environment (anechoic chamber) several items were found to present significant problems for the repeatable acquisition high resolution data. Heretofore some of these items were assumed to be benign.

One such item was the aluminum grate used as flooring in the chamber. This presented two very different problems. The first was that for sound waves at shallow angles of incidence to the grating more surface area was encountered. As such, reflections from the grating were a problem for certain microphone locations. The floor grates between the device under test (DUT) and the base of the array had to be removed (Photo 6).

The second problem caused by the floor grates involved sound traveling normal to the floor in the vicinity of the DUT. The small profile of the grating was sufficiently large and comprised enough total surface area to cause a large magnitude reflection of high frequency energy. Here again the floor grates had to be removed where possible. For the remaining area absorptive treatment was applied to attenuate the reflections to acceptable levels. In addition to this the turntable and its support structure were of sufficient size that they warrant generous amount of absorptive treatment (Photo 7).

A lighting fixture in one corner of the chamber also presented a minor problem. It provided enough reflected energy that a time window needed to be applied to the data. A 20 ms window reduced the level of the reflection so that it does not affect the measured data. This window imposes a low frequency limit and a frequency resolution of 50 Hz on the measured data.

Accurate Microphone Placement

Having the microphones fixed at the proper angular position relative to the DUT point of rotation accomplishes only half of what is necessary for accurate complex data to be measured. The microphones must also be located at the proper radial distance from the DUT point of rotation. The precision of this positioning will determine the upper frequency limit to which the measured phase data is accurate. We will impose a tolerance limit for the phase data of 45° ($\lambda/8$ as discussed earlier). At our high frequency limit of 10 kHz this corresponds to a positioning tolerance of 0.17 inches (4.3 mm). To achieve this level of accuracy for 19 individual microphones at a distance of 4 meters from the POR is no small task.

Another item worth consideration at this point is that of temperature variations. We have been able to greatly minimize the temperature variations with respect to time during the measurement period. However, due to the size of the anechoic chamber a thermal gradient from bottom to top is possible. In fact, one does exist and has been quantified. There is approximately a 5° F difference from the bottom to the top of the chamber. This thermal gradient will alter the speed of a wave front as it passes through it. If all of the microphones were placed at exactly 4.00 m away from the POR the radiation from an omni directional source would reach the upper most mic in the array (0° mic) before it reached the lower most mic (90° mic). This difference in arrival time would cause additional error in the complex (phase) data.

A method was devised for simultaneously solving both of the challenges described above. The exact position of each of the microphones would be determined acoustically. A reference loudspeaker would be aimed directly at each microphone and the IR measured. The 0° mic would be the reference IR. All other mics would be repositioned so that the peak of the IR at that mic would be synchronous with the IR of the 0° mic (Figure 2).

Photo 6 – Floor grates removed from the middle of the chamber

Photo 7 – Absorption on non-removable floor grates and in the well housing the turntable

This would be far more accurate than using a tangible measuring device thus solving the first problem. The acoustical positioning method is actually measuring the arrival time of the wave front and not the distance traveled. Therefore it is naturally self-correcting with respect to any changes in the speed of sound due to temperature gradients.

Any change in the temperature gradient is readily identified by a phase shift in the response measured by the 0° mic. The DUT is oriented so that this microphone is always at 0° (on-axis) or at 180° (diametrically off-axis). This acts as a control during the entire measurement process. It is capable of detecting the slightest amount of change (Figure 3 & Figure 4).

The fact that there is a thermal gradient in the chamber, albeit a small one, necessitates the investigation of the refraction of the wave front while en route to the measurement microphones.[6] Through the application of Snell's Law we can quantify the amount of refraction that occurs for a given differential in the speed of sound.

$$\frac{\sin\theta_1}{\sin\theta_2} = \frac{c_1}{c_2}$$ Snell's Law

* If we allow for a maximum 0.5° change in elevation during propagation due to refraction, the thermal gradient must be kept below 18° F. We have previously quantified the temperature gradient in the chamber to be 5° F. This yields less than 0.2° maximum refractive change in angular propagation. This is a tolerable error for our purposes.

Final Calibration

Type 1 response matched microphones are used in the microphone array. With 19 microphones even the best possible matching will still have some variations. The response variations of the microphones selected for use are all within a 1.5 dB window. This is not sufficient for our purposes.

It was noticed during the initial testing in the chamber that there were large variations in the on-axis measured response of the reference loudspeaker depending on which mic in the array was used. Several other loudspeakers were subsequently measured to verify that directivity of the DUT was not an issue. It was determined that the variations were dependent solely on microphone position. This is understandable given the large measurement distance compared to the overall chamber dimensions.

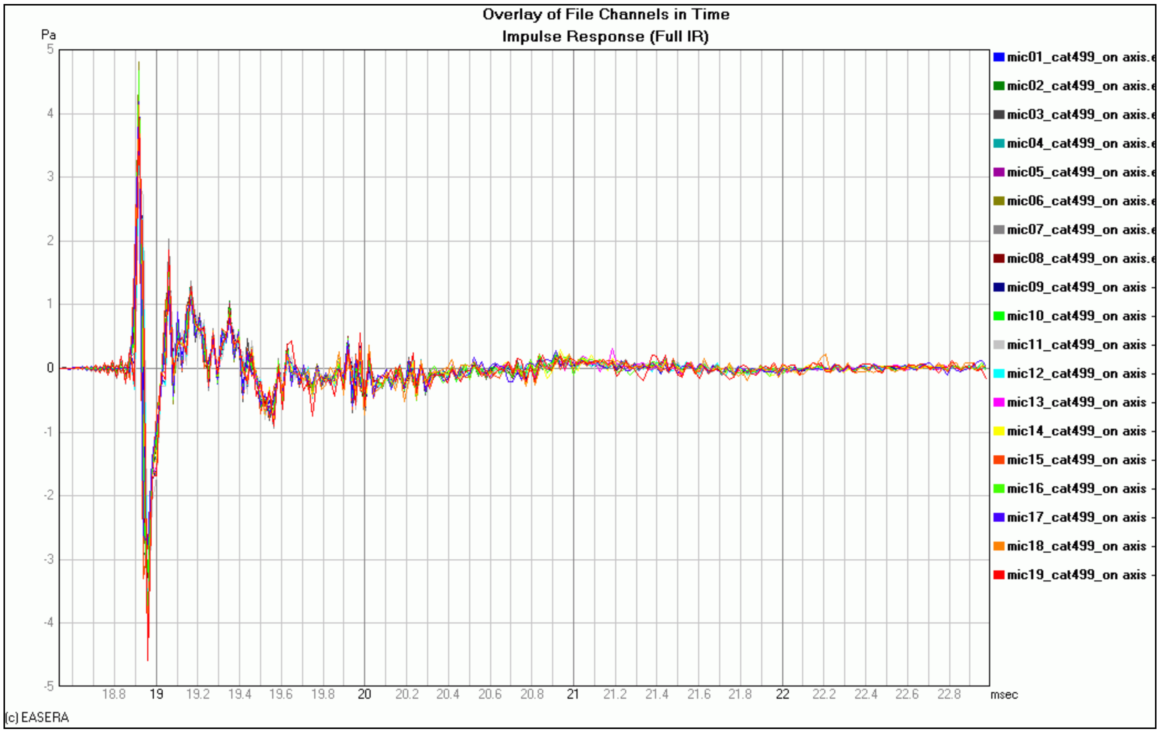

Figure 2 – On-axis impulse response of reference loudspeaker at 19 different microphones

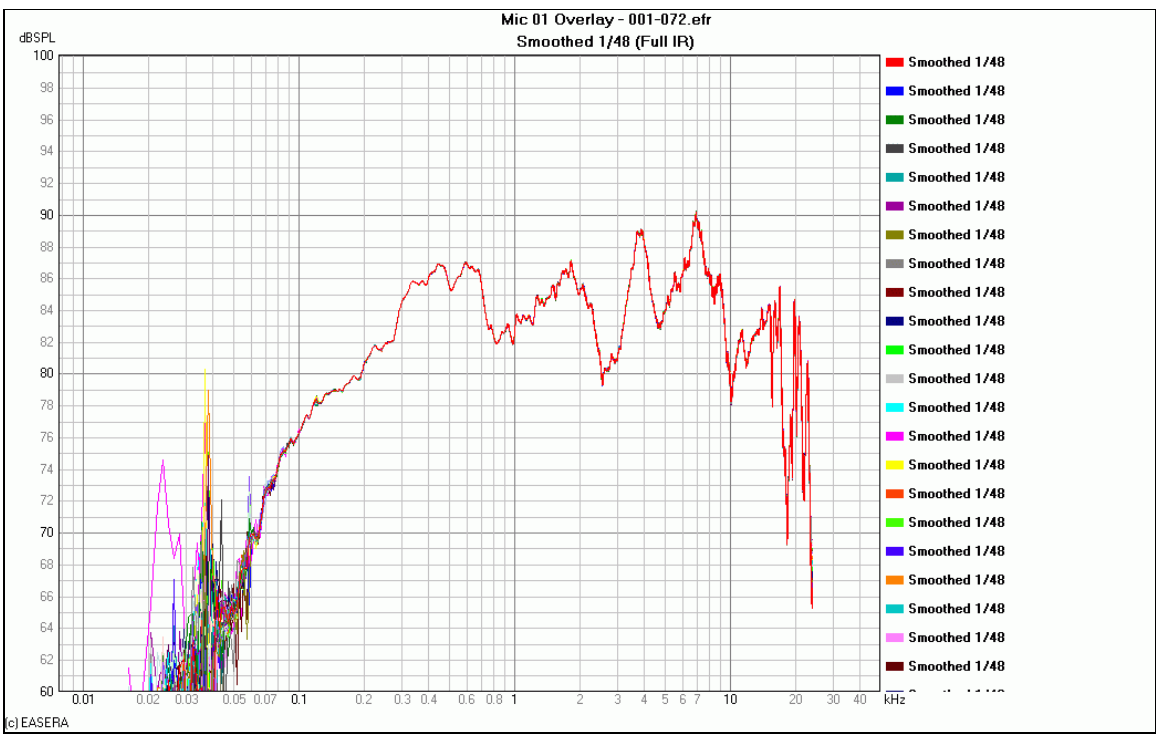

Figure 3 – 72 different frequency response curves of the 0° mic for the front hemisphere of a balloon (Note that the variations are less than 0.25 dB above 90 Hz)

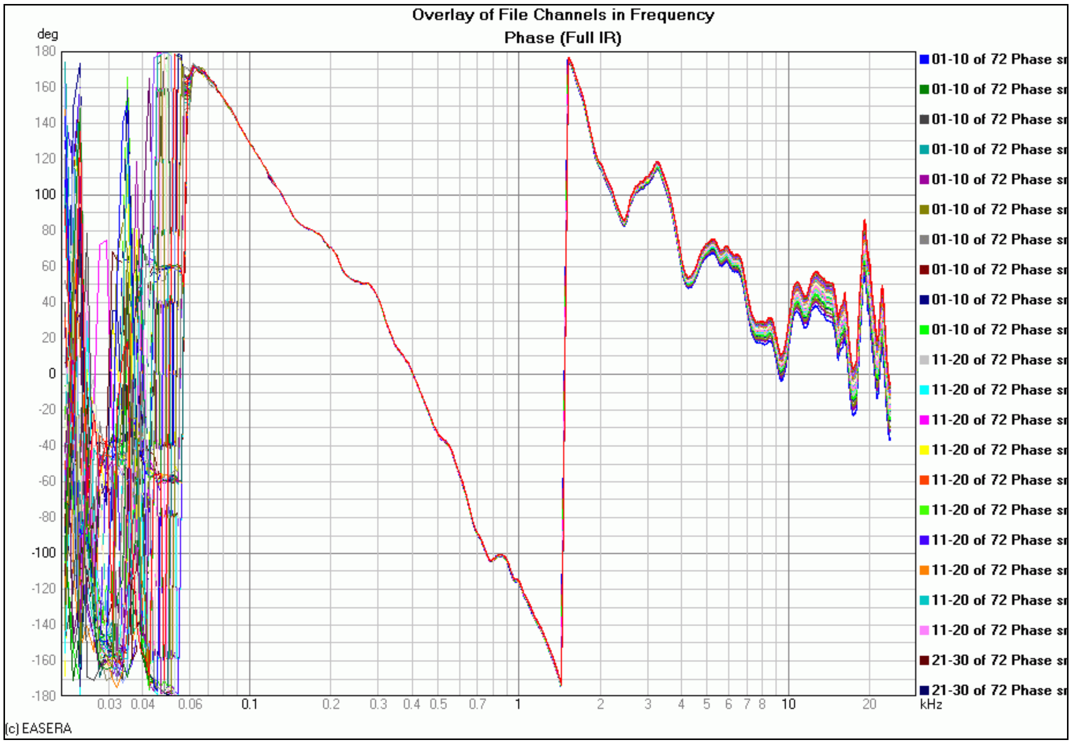

Figure 4 – 72 different phase response curves of the 0° mic for the front hemisphere of a balloon (Note that at 13 kHz all of the curves are within 20° of each other, most of them are within 10°)

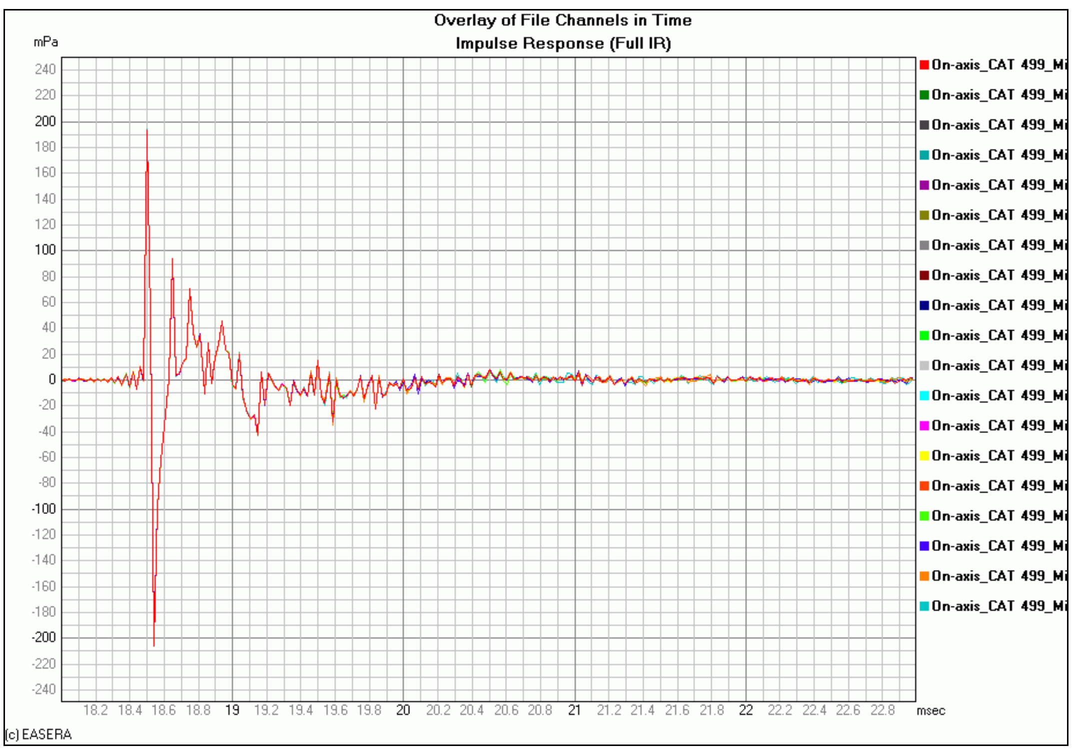

Figure 5 – On-axis impulse response of reference loudspeaker at 19 different microphones using response compensation

Fortunately EASERA has the capability to apply microphone correction in-situ for all measurements. This was a relatively simple matter for the microphone variations as the reference (correction) curves could be obtained from the manufacturer. However, the variations due to mic positioning required a different solution.

A ground plane measurement was performed on the reference loudspeaker outdoors at a distance of 4 m. The loudspeaker was placed above the ground so as to not affect its radiation (diffraction) pattern.[7] The 1/4 inch diaphragm measurement mic was placed on a large piece of glass in the middle of a large parking lot. Our measurement configuration should yield satisfactory results below 13 kHz. At this frequency the measured amplitude error should be less than -0.3 dB. At our upper frequency limit of 10 kHz the error should be less than -0.17 dB. This error is correctable as the function governing it is well known and a simple matter to implement.[8] Similarly, the 6 dB level increase due to the ground plane pressure zone summation is easily negated.

This ground plane measurement would serve as the reference transfer function used to generate correction curves for each of the 19 microphone locations in the array. Thus the response of each microphone at its location in the array would be referenced back to the response of a single microphone in a free field (within our bandwidth limitations). This is the desired measurement condition.

After the response correction curves were generated and implemented the performance of the entire measurement system was verified. This was done by once again measuring the on-axis response of the reference loudspeaker at each of the 19 measurement microphones in its fixed location in the array. All 19 IRs are shown in Figure 5. This can be compared to the IRs in Figure 2 to see the improvements gained by using the response compensation detailed above.

Conclusion

The preceding outlines some of the problems encountered when attempting to accurately measure complex data directivity balloons. The intent is not to imply that the solutions devised by the author, Ron Sauro and others who gave advice are the only ones available; just the ones we used. By using these methods the repeatability of the measured data can be held to within a level of 0.25 dB and phase of 20° from below 100 Hz to greater than 10 kHz.

At the present we believe the accuracy of the one-third octave averaged data supplied for acoustical modeling is within 1.0 dB and 30° of the far field performance. These are limitations imposed by measuring devices, the size of which were outlined in the introduction, at a distance of 4 m. Further work must be done to provide criteria for the maximum cabinet dimensions based on edge diffraction contribution to the directivity when measured at a finite distance.

The author would like to acknowledge and offer his gratitude to Dr. Wolfgang Ahnert, Stefan Feistel, Dave Gunness, Tom McCauley and Jay Mitchell for the generous donation of their time and expertise in the development of this facility and the methods employed.

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[1] S. Feistel & W. Ahnert, The Significance of Phase Data for the Acoustic Prediction of Combinations of Sound Sources, AES 119th Convention Paper, October 2005
[2] Telephone conversation with Dr. Eugene Patronis, September 2005
[3] Kinsler, Frey, Coppens & Sanders, *Fundamentals of Acoustics*, 4th Edition, p. 180
[4] Private correspondence with J.E. Mitchell, September 2005
[5] EASERA is a software program licensed by Software Design Ahnert GmbH of Berlin, Germany
[6] Telephone conversation with Jim Brown, August 2005
[7] Telephone conversation with J.E. Mitchell, May 2005
[8] Beranek, *Acoustics*, p.94

