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Cylinder Measurement Method for Directivity Balloons

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ABSTRACT

There are several ways to obtain the set of frequency responses all around a loudspeaker, the so-called *directivity balloon* which provides useful knowledge about the loudspeaker radiation behavior. In this paper, a novel method for collecting far-field directivity balloon datasets is presented. This alternative method builds on traditional polar measurements and proved to be practical both in terms of measurement time and equipment set-up. By cleverly combining datasets and by using far-field wave propagation, datasets in cylindrical coordinates are created and then projected on a sphere. Eventually, using a spherical interpolation, the directivity balloon is obtained.

1 Introduction

A directivity balloon dataset describes how a sound source radiates into 3D space at a certain radius. For a loudspeaker, it provides a way to extract important parameters such as the traditional horizontal and vertical $-6dB$ coverage angles, the directivity factor and the acoustic power. The frequency response at any point in space in the far-field of the loudspeaker can also be obtained, which makes directivity balloons important for sound system simulation programs. There are a few measurement methods to obtain directivity balloons. In this paper, a novel method is presented, providing a new way to obtain far-field directivity balloons in an acceptable amount of time. It makes use of a simple procedure and some processing involving 3D geometry.

In Section 2, current measurement methods and the associated research will be shortly presented. Then, in Section 3, the far-field directivity balloon and its coordinate system will be defined. The new measurement method will be explained in Section 4.

2 State of the art

Before 3D directivity balloons, directivity data was only available in 2D planes, usually a horizontal and a vertical plane, forming the two main polar responses of a sound source. In the 80's, with the computer power and storage increase, the first 3D directivity balloons appeared and brought all the rest of the spatial information which traditional polar plots were missing. Simulated 3D directivity balloons were introduced ([1]). Later, real-world measured 3D directivity balloons appeared as well as the first graphic sound system design programs using these datasets ([2] and [3]).

2.1 Current measurement methods

The most straightforward method to obtain the directivity balloon is to directly measure the source response at all the points on the sphere defining the balloon dataset ([4]). This can be done with a microphone moving around the source to capture the response at every point needed. Equivalently, one can use a moving source and a microphone at a fixed position. Alternatively, a sphere discretely sampled with microphones can be placed around the source in order to measure all points at once. In practice, one can use a combination of moving parts and microphone arrays: usually, an arc-array of microphones is used along with a rotary table on which the source is mounted.

Recently, a new method was introduced ([5]). It consists of scanning the near-field all around the source at a very close distance. Then, a set of spherical harmonic modes of a given order can be fitted to the measured near-field. This expansion can finally be used to extract any balloon beyond the measurement distance, and in particular, the far-field directivity balloon.

2.2 Additional research

The directivity balloon measurement methods are traditionally performed in an anechoic environment because otherwise there are unwanted acoustic reflections in the measured impulse responses. Nonetheless, measuring in a non-anechoic environment is still possible as there exist some techniques to remove these reflections. For instance, measurements of impulse responses can be time-windowed to remove the undesired reflections. This method works best at high frequencies. At low frequencies, field separation techniques can be used ([6] and [7]).

Some additional research papers on directivity balloons' reliability, especially when used in sound system simulation programs, have added more knowledge to the topic. For instance, it has been shown that using complex data rather than magnitude-only data led to large improvements in accuracy when simulating the radiation of several sound sources used together ([8]).

3 Definitions

3.1 Directivity balloon

A balloon dataset is a collection of the frequency responses of a sound source in every direction around it and at a given distance. The data includes the magnitude and sometimes also the phase of the radiated sound waves in the frequency range of interest.

In this paper, the focus is on *far-field balloons* as they are used by many acoustic simulation programs. It is well known that, using the far-field approximation, any sound source can be modelled as an equivalent point-source with spherical wave expansion and sound pressure varying inversely as distance. This results in a directivity pattern which is constant with distance. Therefore, the sound pressure at any distance can be extracted from a single balloon dataset, provided that the far-field approximation is valid. To do so, it is simply a matter of taking the measured frequency response in the direction of interest and applying the classic phase and magnitude propagator $Ae^{j\varphi}$, j being the unit imaginary number. A and φ are respectively the magnitude and the phase correction factors defined as

$$\varphi = \frac{\omega(r_1 - r_2)}{c} \quad and \quad A = \frac{r_1}{r_2}, \tag{1}$$

where ω is the angular frequency, c the speed of sound, r_1 the reference directivity balloon radius (usually 1m) and r_2 the wanted distance from the source.

3.2 Balloon coordinate system

To fully and uniquely locate a balloon dataset in 3D space, a coordinate system must be defined. In this regard, a reference point, a principal axis of radiation and an orientation must be chosen for the sound source.

It seems desirable to choose the reference point as the acoustic center of the sound source, especially if a far-field balloon is wanted. Unfortunately, the question of the exact location of the acoustic center is a complex topic ([9]), and some sound sources such as multi-way speakers can have several acoustic centers. However, given the error distance between the chosen reference point and the actual acoustic center, critical upper frequencies of validity have been defined ([10]) and the authors have shown that errors on the acoustic center location do not have a significant impact on the results, as long as phase data is taken into account.

From the reference point, the principal direction of radiation is chosen and defines the positive Z coordinates. Finally, regarding the choice of the

orientation, when looking at the sound source from the front, its right-side shall point towards the positive X coordinates and its top-side towards the positive Y coordinates. From this Cartesian coordinate system, one can define the associated spherical coordinate system with the elevation angle φ oriented along the Z-axis and the azimuth angle θ starting at the right side of the sound source and revolving around it following the right-hand rule along the positive direction of the Z-axis.
A balloon dataset can be stored in a three-dimensional matrix:

1. The elevation angle ranging from $-90°$ at the back of the sound source to $+90°$ at its front.
2. The azimuth angle ranging from $0°$ to $360°$ starting on the right side of the sound source.
3. The frequency.

Each dimension features a specific resolution: angular resolutions for the two spatial dimensions (elevation and azimuth) and spectral resolution for the frequency. The spatial sampling of a directivity balloon with a 5° angular resolution in both azimuth and elevation angles is shown in Figure 1.

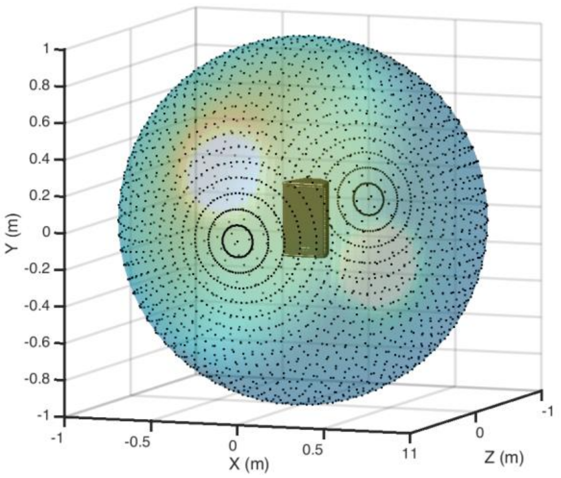

Figure 1. Spatial sampling for a directivity balloon dataset with a 5° resolution. Note that the location of the points defines an orientation for the sphere along the principal axis of radiation, resulting in a denser sampling at the poles than at the equator.

4 Cylinder measurement method

4.1 Principle

4.1.1 Data collection

The measurement method described in this paper allows to measure the full complex far-field directivity balloon of a loudspeaker in a decent amount of time. The measurement is performed in an anechoic chamber, using one or two microphones, and involves some post-processing.

The idea is to collect a set of polar measurements and create a balloon dataset from it.

A polar measurement contains the directivity data sampled on a circle. This data is easily collected using a fixed microphone and by placing the sound source on a rotating system. With the simple addition of a translation system perpendicular to the rotation plane, one can perform polar measurements at several heights and therefore obtain directivity data on a cylinder (Figure 2a).

The next step is to get data on the sphere. Using the far-field approximation, one can use the propagator term defined in Equation 1 to project measurement points backwards onto the sphere: the distance correction is equal to $r_2 - r_1 = \sqrt{H^2 + R^2} - R$, where H is the height and R the radius of the sphere.

As can be seen in Figure 2c, this method does not lead to constant steps in angular elevation. In order to correct for this, the elevation steps can be distributed in a better way with the following formula: $H(\alpha) = R\tan(\alpha)$ where α is the elevation angle ranging from $-90°$ to $+90°$ with the desired elevation angular step (Figure 2b and 2d).

However, it is not possible to cover the full sphere because it would require an infinitely long cylinder in order to obtain the points at the top and at the bottom of the sphere. Therefore, the idea is to combine data points from two orthogonal cylinders in order to get data on the entire sphere. With a height comprised between $H_{min} = -R$ and $H_{max} = R$, a cylinder covers a portion of the sphere corresponding to the

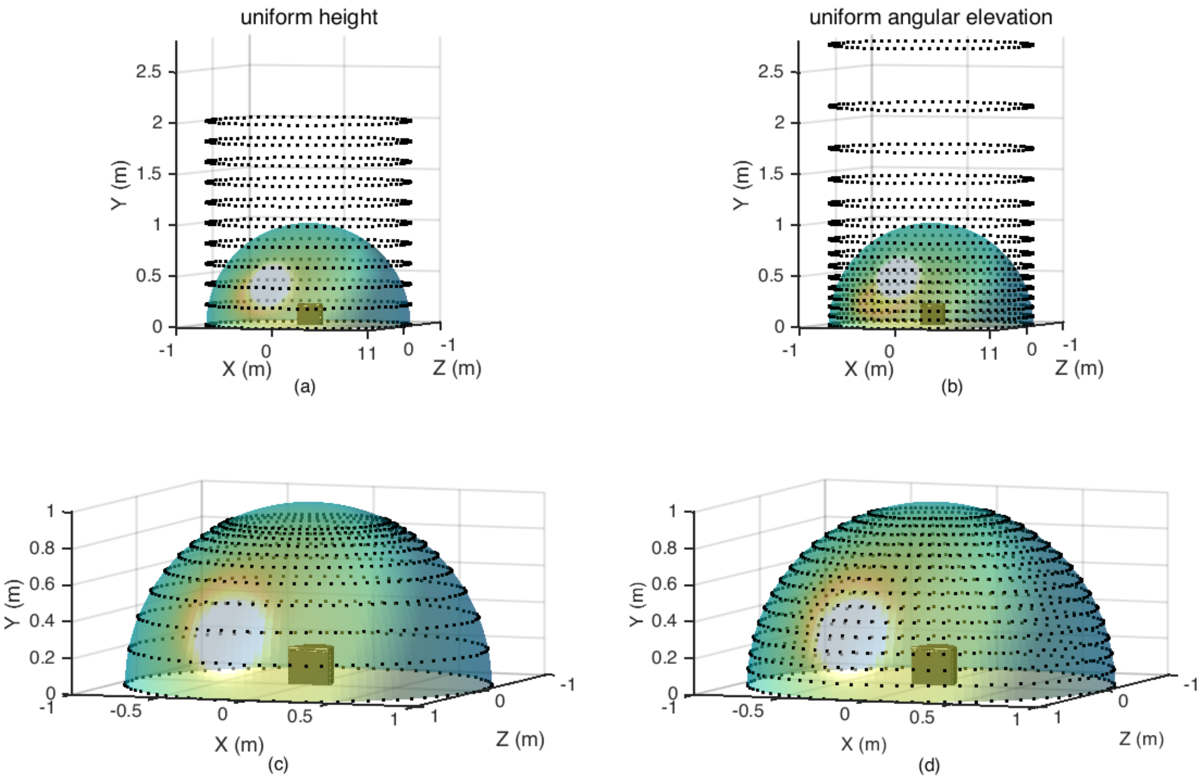

Figure 2. Two methods of elevation sampling (a and b) and their derived projection on the sphere (c and d). Black dots correspond to sampling points. Only positive values of elevation are represented for the sake of clarity.

range $-45°$ to $+45°$ for α. Thus, by measuring a cylinder along the height of the loudspeaker and another one along its width, the full directivity sphere can be covered (Figure 3).

The sphere can be split into three portions:

1. The right and left “caps” of the sphere are covered with data points coming only from the first cylinder.
2. The top and bottom “caps” of the sphere are covered with data points coming only from the second cylinder.
3. The remaining portions of the sphere feature data points coming from both cylinders.

4.1.2 Spherical Interpolation

It can be observed that the measured data points do not lie at the exact locations of the actual data points defining the directivity balloon (see Figure 4). This is because the directivity balloon is oriented towards the positive Z-axis whereas the two cylinders were measured along the Y-axis and the X-axis. To obtain the directivity balloon data points, an interpolation on the surface of the sphere becomes necessary.

As a first approach, the Inverse Distance Weighting method presented in [11] is directly implemented because it has proven useful for directivity balloons. It is based on a weighted average of the inverse of the great-circle distances (shortest distance between two points on the surface of a sphere) from the wanted point to all measurement points. A variation of this

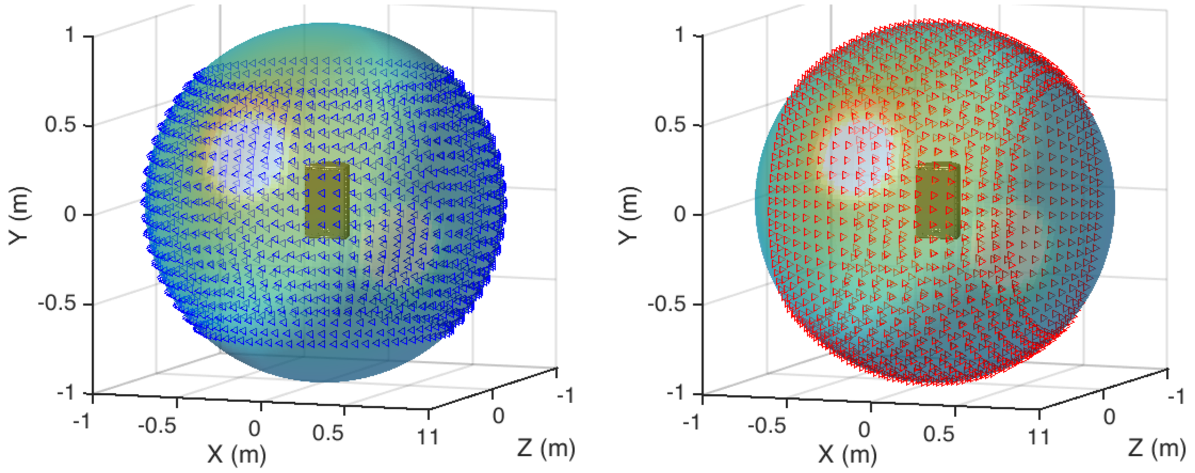

Figure 3. First cylinder's measurement points along the height (left plot) and second cylinder's measurement points along the width (right plot).

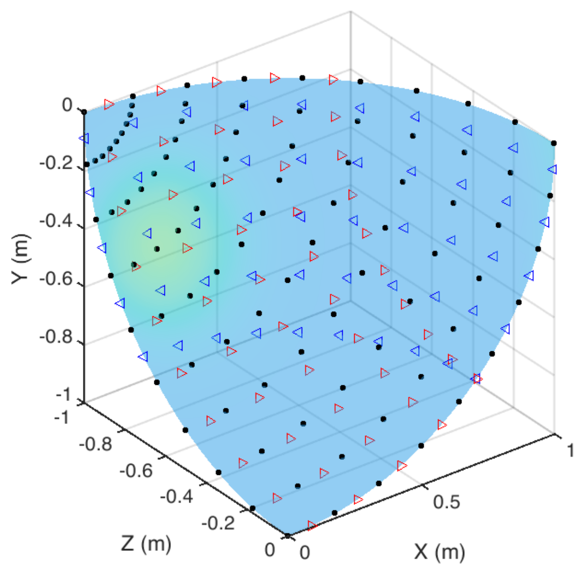

Figure 4. Portion of the sphere. Blue (left-pointing triangle) and red (right-pointing tringle) markers respectively correspond to first cylinder and second cylinder measurement data. Black dots define the directivity balloon data points.

method consists in considering only half of the sphere (the hemisphere centered on a given target) and this can be generalized to any solid angle by setting an appropriate threshold.

Other methods come from the meteorology field, where this computational geometry problem is well-documented ([12]). Some of them involve mapping the surface of the sphere on a plane using a map projection, then performing the interpolation using traditional 2D techniques. There are several map projections available ([13]); in this paper, the *equirectangular* projection is chosen. This method uses the elevation and the azimuth values as the new Cartesian orthogonal coordinate system (see Figure 5). Even though this projection features large distance distortions at the poles, it is chosen for its straightforward implementation and because it allows to map the entire sphere onto a single plane. Once projected, the data is interpolated using a 2D cubic algorithm which degree of smoothness and continuity is assumed to provide a realistic representation of the sound pressure all over the sphere.

For both the Inverse Distance Weighting method and the map projection method, amplitude and continuous (unwrapped) phase are interpolated separately as it has been shown to be the adequate method when

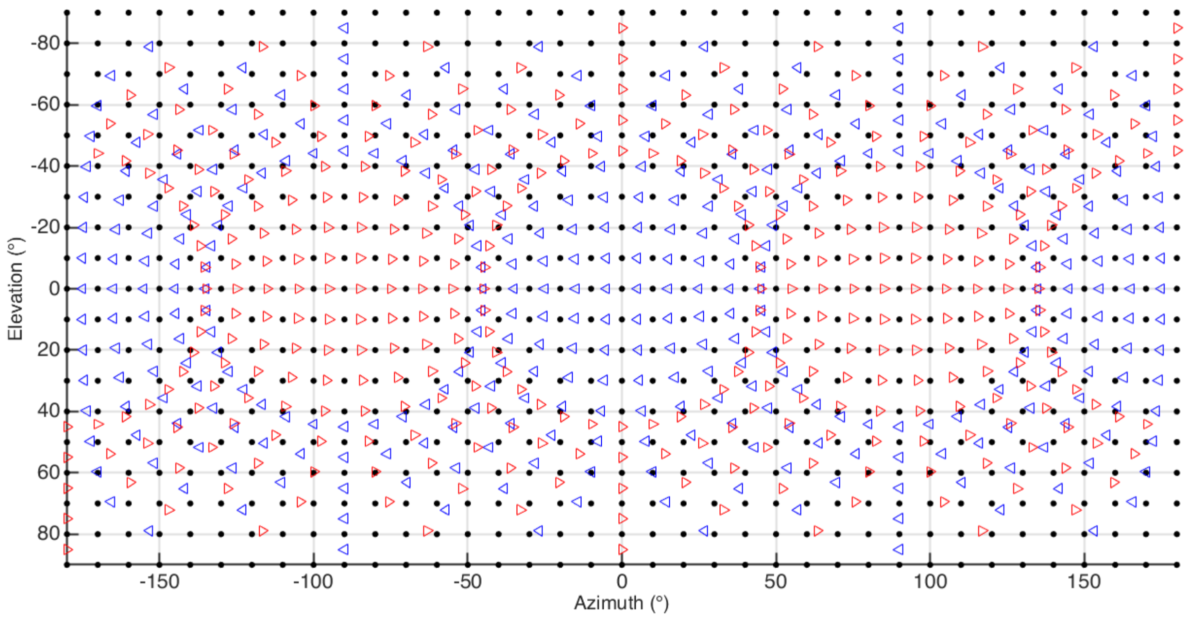

Figure 5. Equirectangular projection of the measurement data and the wanted data. Same markers used as in Figure 4.

dealing with complex-valued frequency response data ([14]).

Finally, in order to ensure a smooth connection between data from both cylinders, an additional rule is introduced. In the first two portions of the sphere defined earlier, only points coming from the corresponding cylinder are used. In the third portion, where there are measurement points coming from both cylinders, the interpolation is calculated twice: once with each cylinder's points. Then the two complex values obtained are averaged (amplitude and continuous phase separately) using weights defined by the following heuristic scheme:

$$W_1 = \frac{1}{2}\left(\cos\left(\frac{\pi Y}{2}\right)^2 + \sin\left(\frac{\pi X}{2}\right)^2\right) \quad and$$
$$W_2 = \frac{1}{2}\left(\cos\left(\frac{\pi X}{2}\right)^2 + \sin\left(\frac{\pi Y}{2}\right)^2\right), \tag{2}$$

W_1 and W_2 respectively being used for the first and the second cylinder's measurement points. X and Y are respectively the horizontal and the vertical coordinates of the target point. These weights are defined such that $W_1 + W_2 = 1$. This scheme has two advantages:

1. It provides a smooth transition between the data coming from the two cylinders
2. It favors the measurement points close to the vertical and the horizontal planes which contain the main traditionally-measured polar measurements. These planes also correspond to measurement positions where the microphone was the closest (implying a lower correction distance) and incidence angles were the smallest (reducing the influence of the microphone polar pattern).

The results show no significant difference between the Inverse Distance Weighting method and the equirectangular projection method. Therefore, the latter is chosen for its simplicity and computational efficiency.

4.2 Application to a real case

4.2.1 Practical concerns

The measurement is performed in a full anechoic chamber. The distance from the elevation axis to the microphones is fixed to $r = 2\text{m}$. The loudspeaker being measured is an ID24 from NEXO as its geometric construction and its asymmetric 120°/40° horn lead to a very distinct radiation pattern. There is no universal approximation for the far-field critical distance but the two criteria $r \gg a$ and $r > \frac{\pi a^2}{\lambda}$ where λ is the wavelength and a is the radius of a piston radiator, are frequently used ([15]). The loudspeaker measured has a maximum dimension of 300mm, therefore, using $a = 150\text{mm}$, the far-field assumption can be made up to around 10kHz.

As can be seen in Figure 6, two microphones are used instead of one. This allows to reduce the translation needed for the elevation system as well as the height of the anechoic chamber by a factor of two. Indeed, when the loudspeaker goes up, the bottom microphone will cover the lower portion of the cylinders whereas the top microphone will cover the top portion of the cylinders. However, elevation steps defined earlier cannot be achieved anymore for both microphones at the same time. While the bottom microphone requires elevation steps defined by $s_1(\alpha) = R\tan(\alpha)$ with α ranging from 0° to 45°, the top microphone requires steps defined by $s_2(\alpha) = R\left(1 - \tan\left(\frac{\pi}{4} - \alpha\right)\right)$. Therefore, in order to avoid biasing one microphone, an average step value is used:

$$\begin{aligned} s(\alpha) &= \frac{s_1(\alpha) + s_2(\alpha)}{2} \\ &= \frac{R}{2}\left(1 + \tan(\alpha) - \tan\left(\frac{\pi}{4} - \alpha\right)\right). \end{aligned} \tag{3}$$

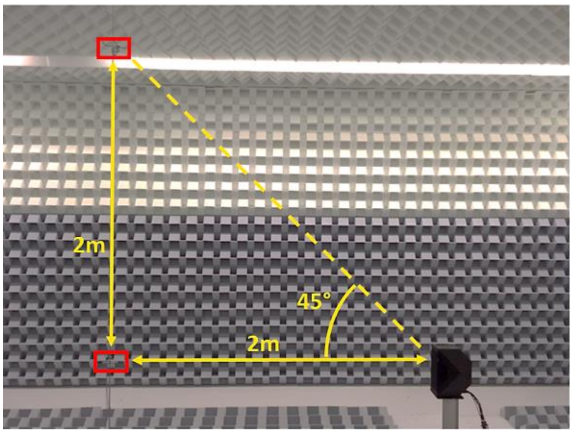

Figure 6. Setup of the directivity balloon measurement. Red rectangles show the location of the two microphones.

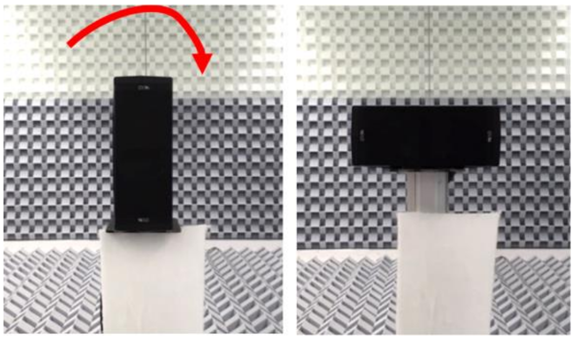

Figure 7. Loudspeaker positioning for the measurement. Left: first cylinder. Right: second cylinder.

The measurement is performed by automatically driving the rotary table and the lift table when needed. At this stage of development, the speaker had to be manually rotated 90° between the first cylinder and the second cylinder measurement, making the whole procedure semi-automated (see Figure 7).

4.2.2 Result example

Once the data is collected, the post-processing described in the previous section is applied to get the final directivity balloon. For example, it allows to obtain a 2.5° resolution complex directivity balloon dataset in approximately an hour. The time for post-processing is typically in the range of minutes. An example can be seen in Figure 8.

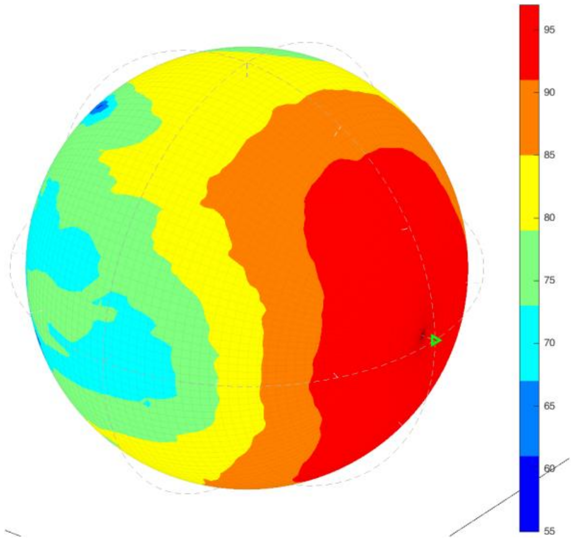

Figure 8. Example balloon plot with 2.5° resolution at f=3650Hz. At this frequency, the dispersion is mainly due to the asymmetric horn (120° vertical, 40° horizontal). Scale in dB SPL.

5 Summary

A novel measurement method to obtain full complex directivity balloon datasets has been developed. This method allows to measure a loudspeaker directivity balloon in an anechoic chamber with two microphones, a rotary table and a lift table, using some post-processing and in a relatively short amount of time.

The next step is to evaluate the quality of the results of this method compared to traditional methods.

6 Acknowledgements

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