DATASHEET

Beamformer Data

Specification for Eigenmike Software Beamformer

Version 2

Rev. A

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1. Introduction

The em32 Eigenmike® microphone array is capable of capturing a soundfield with a high degree of spatial accuracy. The 32 raw microphone signals can be processed into Eigenbeams (a.k.a. spherical harmonics, Ambisonic signals) and then linearly combined to form microphone beampatterns up to 4th order. The beamforming process allows the beampatterns to be steered in any direction in 3D space and focus on specific directions in the acoustic field. Beamforming software for the em32 Eigenmike microphone array is available via the stand-alone EigenStudio® application or the EigenUnits® plugins.[1] See the "EigenStudio User Manual"[2] and "EigenUnits User Manual"[3] documents for more details.

The following document details some of the main characteristics of the beampatterns produced by the beamforming process using mh acoustics' software. This document presents definitions, conventions, and performance specifications, as well as discussion of the overall beamforming process.

[1] http://mhacoustics.com/download

[2] http://mhacoustics.com/sites/default/files/EigenStudio User Manual R02B.pdf

[3] http://mhacoustics.com/sites/default/files/EigenUnits User Manual R01D.pdf

2. Definitions and Conventions

2.1 Spherical Coordinate System

For the em32 Eigenmike array, the following conventions are used when defining the spherical coordinate system (see Figures 1 and 2):

- **Vertical Angle** (ϑ): is the angle in the vertical dimension. In degrees it ranges from 0 to 180. The 0 degrees direction points away from the top of the spherical array (the opposite side from where the shaft mounts to the Eigenmike array; towards the ceiling in a typical arrangement or equivalently the positive z-axis in spherical coordinates). The horizontal plane is in the 90 degrees direction, and the 180 degrees direction is in the direction of the shaft (typically towards the floor or also the negative z-axis in spherical coordinates).

- **Horizontal Angle** (φ or ϕ): is the angle in the horizontal plane (the x-y plane in spherical coordinates). It ranges from 0 to 360 degrees. The 0 degrees direction aligns with the "mh acoustics" logo on the shaft of the Eigenmike array. The angle increases in the counter-clockwise direction looking from the top of the Eigenmike array.

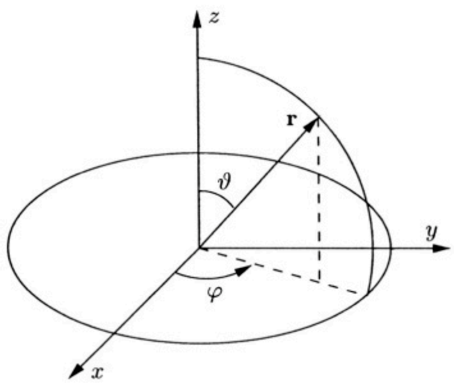

Figure 1: Spherical Coordinate Conventions

Figure 2: Coordinate Axes w.r.t. em32

3. Beamformer Description

The following sections detail processing and performance specifications for the beamformer available in the latest versions of the Eigenmike software[4]. The data presented here represents the cumulative output of the signal chain comprising the em32 microphone array and the associated signal processing software (i.e. EigenStudio or EigenUnits). The data has been derived from simulations using the actual software implementation, and has been proven to agree well with real-world measurements made of the em32 microphone array.

[4] EigenStudio v2.8.5 and EigenUnits v0.9, May 2017

3.1 Overview

An overview of the signal chain comprising the complete beamforming process is shown in *Figure 3*. Upon streaming into the Eigenmike software, the 32 raw microphone signals are calibrated based on the factory-measured calibration values that are stored in firmware inside each em32 array. These values are used to compensate for microphone amplitude mismatch to improve subsequent beamformer performance.

Next, the 32 calibrated microphone signals are encoded into Eigenbeams, up to 4^{th} order, by the *Eigenbeam Encoder*. For more information about the Eigenbeam encoding process and performance, please see the "Eigenbeam Datasheet"[5].

The encoded Eigenbeams are then input to the *Modal Beamformer*, which linearly combines the Eigenbeams in order to realize the desired beampattern. This module also handles the steering of the beampattern in 3D space. See Section 3.2.

A parallel path to the encoding/beamforming signal processing implements the high-frequency extension (*HF Extension*) for signals above 9 kHz. The high-frequency extension signal path is discussed in more detail in the Section 3.3.

Finally, the main beamformer output and high-frequency extension path output signals are combined via a crossover to realize the full-band output signal.

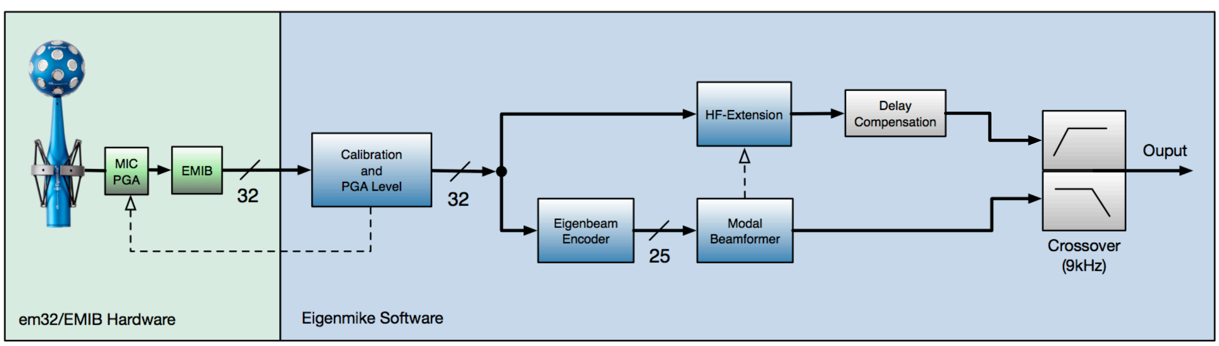

Figure 3: Beamformer Signal Flow

[5] https://mhacoustics.com/sites/default/files/Eigenbeam%20Datasheet_R01A.pdf

3.2 Modal Beamformer

The *Modal Beamformer* linearly combines the Eigenbeams to realize the desired beampattern. This module also handles the steering of the beampattern in 3D space.

The following microphone beampatterns are available:

- **Omnidirectional** (0^{th} order) – Equal sensitivity in all directions
- **Cardioid** (1^{st} – 4^{th} order) – Null(s) at 180°
- **Supercardioid** (1^{st} – 4^{th} order) – Maximum front-to-back power ratio
- **Hypercardioid** (1^{st} – 4^{th} order) – Maximum directivity
- **Dipole** (1^{st} order) – Maximum sensitivity at 0°/180°. Nulls at 90°/270°

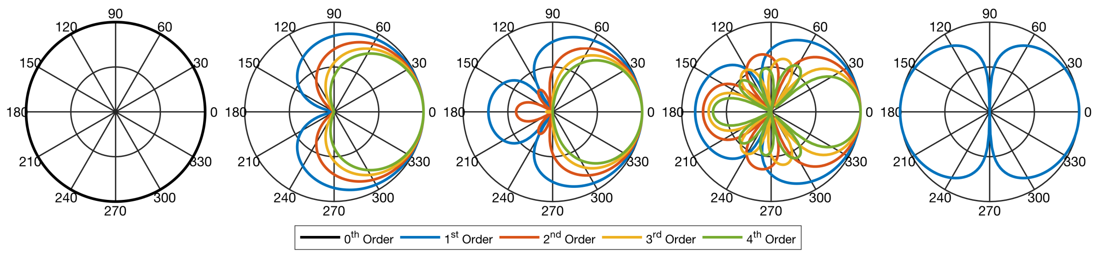

Figure 4: Comparison of Beampattern Types

(from left to right: Omnidirectional, Cardioid, Supercardioid, Hypercardioid, Dipole)

In practice, the higher-order beampatterns are restricted to limited operating frequency ranges in order to ensure a minimum beampattern SNR threshold is achieved. Thus using a white-noise-gain constrained design results in higher-order beampatterns that effectively “fall back” to progressively lower-order beampatterns at lower frequencies. This smooth transition can be seen in the Beamformer Specification plots in Section 4.

The *Modal Beamformer* is designed so that the beampatterns have a nominally flat on-axis magnitude frequency response. Note that additional application-specific equalization may be required and should be applied externally as needed. Since the beamformer is an entirely linear, time-invariant process, any EQ can be applied either to the raw input signals, or, more efficiently, directly to the beamformer output signal.

3.3 High-Frequency Extension

In parallel to the main beamforming signal path, an additional signal path implements a "high-frequency extension" as depicted in *Figure 3*. Due to the fixed geometry of the sensors on the sphere, a *spatial* Nyquist frequency exists beyond which the beampatterns become significantly *spatially* aliased, degrading the desired spatial characteristics of the beamformer.

To overcome this, the high-frequency extension is used to replace the spatially aliased portion of the main beamformer's output signal with a more spatially defined beampattern that is steerable in 3D space. As seen in *Figure 3*, the main beamformer output and high-frequency extension path output signals are combined via a crossover to realize the complete output signal.

The *HF Extension* module is linked to the *Modal Beamformer* to allow choosing a lower or higher directivity extension beampattern appropriate for pairing with the main beamformer's beampattern. Furthermore, steering information about the main beamformer's steering direction is communicated to the *HF Extension* to allow steering of the high-frequency extension pattern towards the desired beam direction[6].

Finally, additional delay and equalization is applied to the high-frequency extension signal path in order to match the main beamformer signal path and desired frequency response. The delay is realized internally in the EigenStudio software; however, when using the modular EigenUnits plugins, it is critical that the user implement this delay explicitly in their audio processing software (DAW). For more information, please see the "EigenUnits User Manual"[7].

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[6] Note that even the omnidirectional beampattern - which by definition does not favor a specific look direction – should still provide steering information to the *HF Extension.* The *HF Extension* always has some directivity, so it is advisable that the user still specify a look direction when using the omnidirectional pattern. This is analogous to the setup and pointing of a traditional single-diaphragm omnidirectional microphone, which also typically has some directivity as wavelengths begin to "see" the microphone.

[7] https://mhacoustics.com/download

4. Beamformer Specification

In this section details are given on the performance of each of the individual microphone beampatterns available in the Eigenmike software[8]. Details are given regarding their spatial and spectral response, and other performance metrics.

All beampatterns are shown steered to the nominal angle of ϑ=90°, φ=0°. For a typical orientation of the em32 microphone array, this corresponds to a beam in the horizontal plane pointed in the forward direction, along the positive x-axis (see Section 2.1). The *Frequency Response*, *Directivity Index*, and *Beampattern SNR* plots all show the value of these metrics for this look direction.

4.1 Metrics and Plot Types

4.1.1 Spatial Response

The microphone spatial responses are depicted in multiple ways: a *3D Balloon* plot (for basic reference only), a *Waterfall of Directivity* plot, and standard *Polar Diagram* plots. The waterfall plot shows the directivity variation across both angle and frequency, and is one of the more comprehensive representations of the spatial response. However, it is more difficult to interpret with accuracy since the response amplitude is represented by color.

The *Polar Diagrams* allow for a more accurate interpretation of spatial response at a specific angle of incidence; these are displayed for a select group of frequencies. Per standard practice, all polar diagram plots are normalized to the maximum sensitivity in the displayed plane. Polar patterns for frequency regions that lie within the high-frequency extension are shown with dashed lines.

Both the *Waterfall* and *Polar Diagram* plots show the directivity of the beampattern in a 2D plane (e.g. the horizontal plane when the beampattern is steered to ϑ = 90° and ϕ= 0°). Since the available microphone beampatterns are axisymmetric around the axis pointing in the look direction, the spatial response remains the same in all other planes by this rotation.

4.1.2 Directivity Index

The *Directivity Index* plots show the 3D directivity index. The directivity index (DI) is a useful measure of the amount of directional gain of the array in a spherically diffuse sound field. It gives the amount of SNR increase due to the beamformer in a spherically isotropic noise field.

Given the beamformer response, $E(\omega,\vartheta,\varphi)$, the directivity index at angular frequency ω, and look direction $[\vartheta_0,\varphi_0]$ is given by:

$$DI(\omega,\vartheta,\varphi) = 10\log\left[\frac{4\pi|E(\omega,\vartheta_0,\varphi_0)|^2}{\int_0^{2\pi}\int_0^{\pi}|E(\omega,\vartheta,\varphi)|^2\sin\vartheta\, d\vartheta d\varphi}\right]$$

[8] All plots depict the performance in EigenStudio when using the 0dB WNG setting.

4.1.3 Beampattern SNR

The *Beampattern SNR* plots show the *change* in SNR for the realization of a specific beampattern *relative to the SNR of a single microphone capsule.* This is referred to as the white-noise-gain. The white-noise-gain (WNG) is an important metric in beamformer performance. The white-noise-gain can be used to quantify the output SNR of the beamformer from knowledge of the noise of the microphone and electronics used in the beamformer.

A positive white-noise-gain indicates that the beamformer output SNR (where the noise here is uncorrelated self-noise between the channels and not spatial noise) will be higher than the SNR of single microphone element. Similarly, a negative white-noise-gain indicates that the output SNR of the beamformer will be lower than that of a single microphone element. A white-noise-gain of 0 dB means that the beamformer output will have the same SNR as a single microphone element (where there is an implicit assumption that each microphone element has the same SNR).

The absolute SNR of the beampattern can be calculated by adding (in dB) the beampattern's WNG value to the individual microphone capsule SNR as specified by the hardware datasheet[9,10].

4.1.4 Beamwidth

Finally, the *Beamwidth* plots depict the 3dB beamwidth. The beampattern's beamwidth is defined as the angle enclosed between the -3dB points (relative to the main beam peak direction) in the beampattern's directional response.

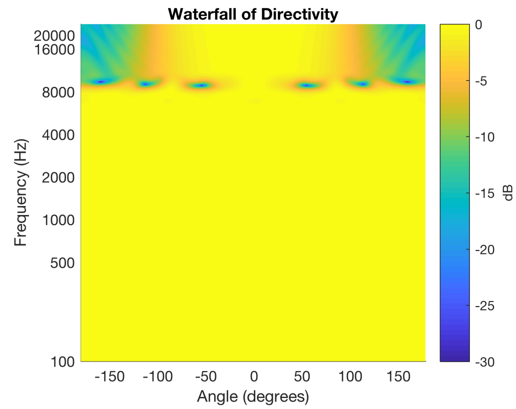
4.2 Specification Data

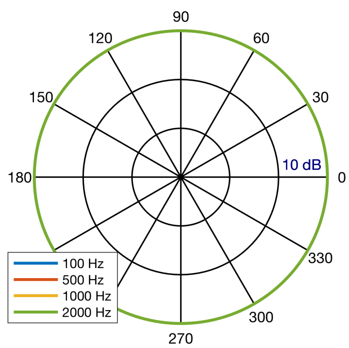
The beamformer specification data for each beampattern is shown on the following pages.

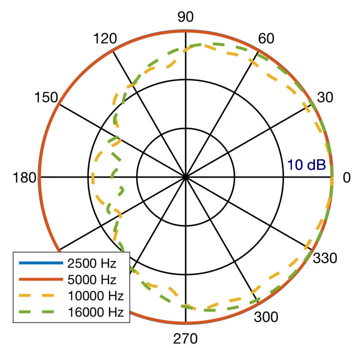
[9] Refer to the "em32_datasheet" included with the em32 hardware for more details.

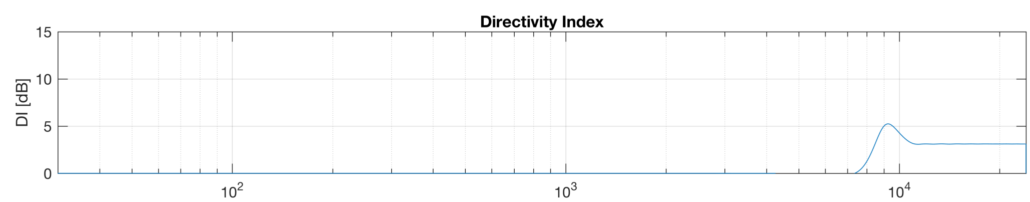
[10] For example, the beamformer for the 1st-order cardioid has a WNG of approximately +15dB at 1kHz. Using individual microphone capsules with an SNR of 79dBA (15dBA ENL) would then yield an absolute SNR for this beampattern of 79+15= 94dB at 1kHz.

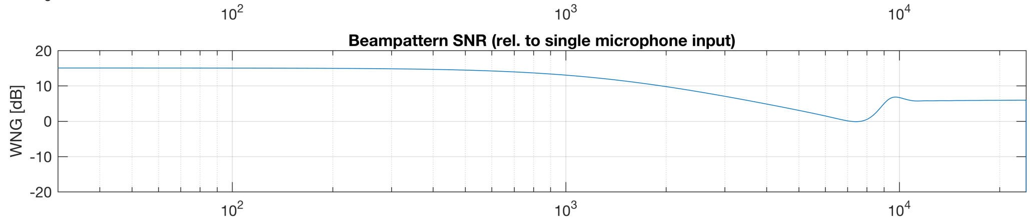
0th-order Omnidirectional

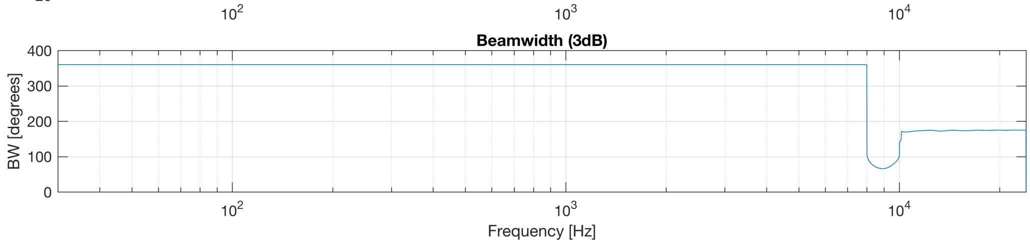




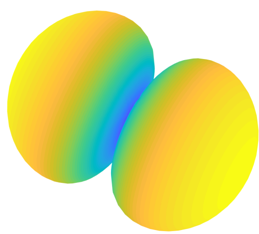


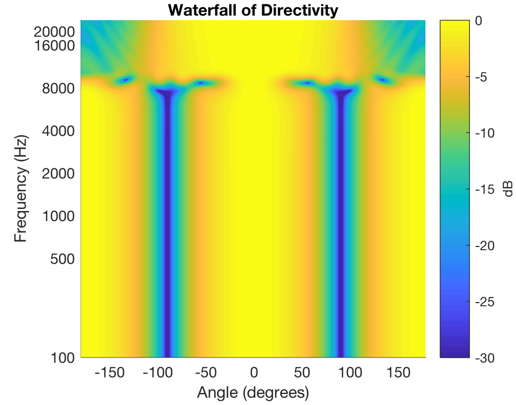


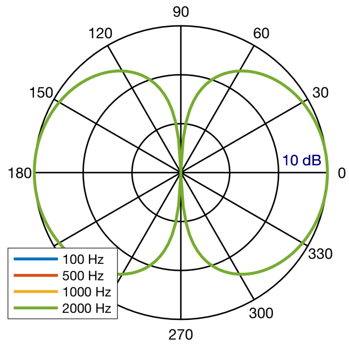


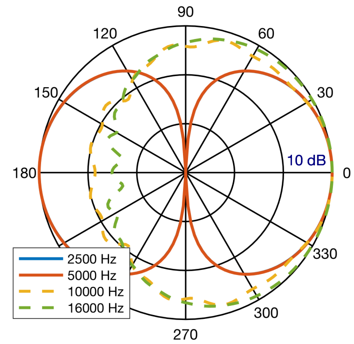


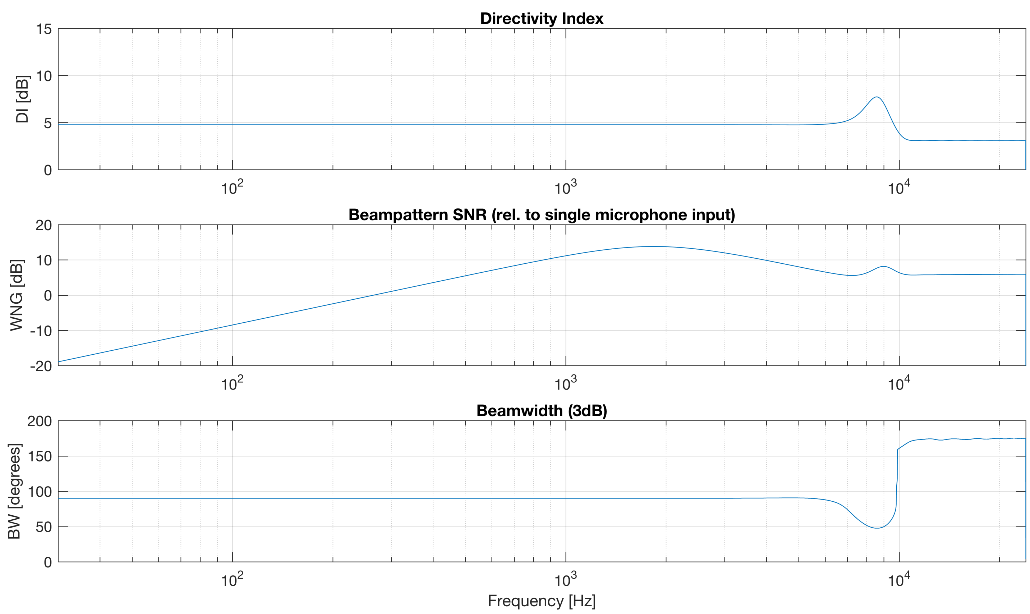
1st-order Dipole



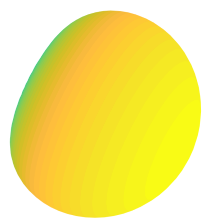


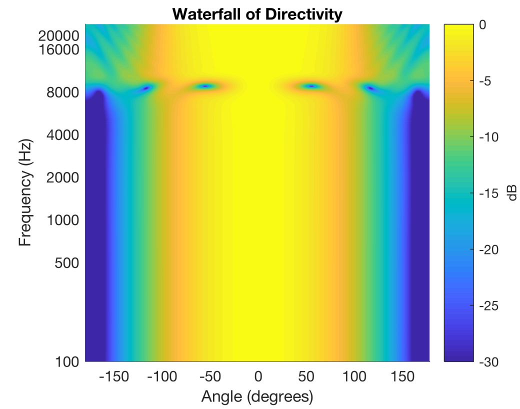


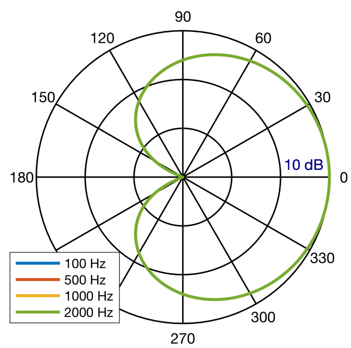


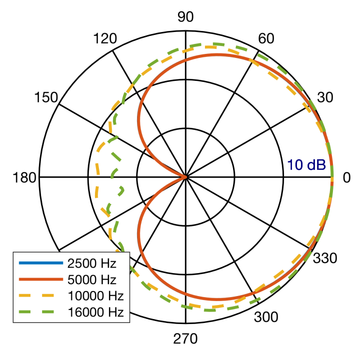


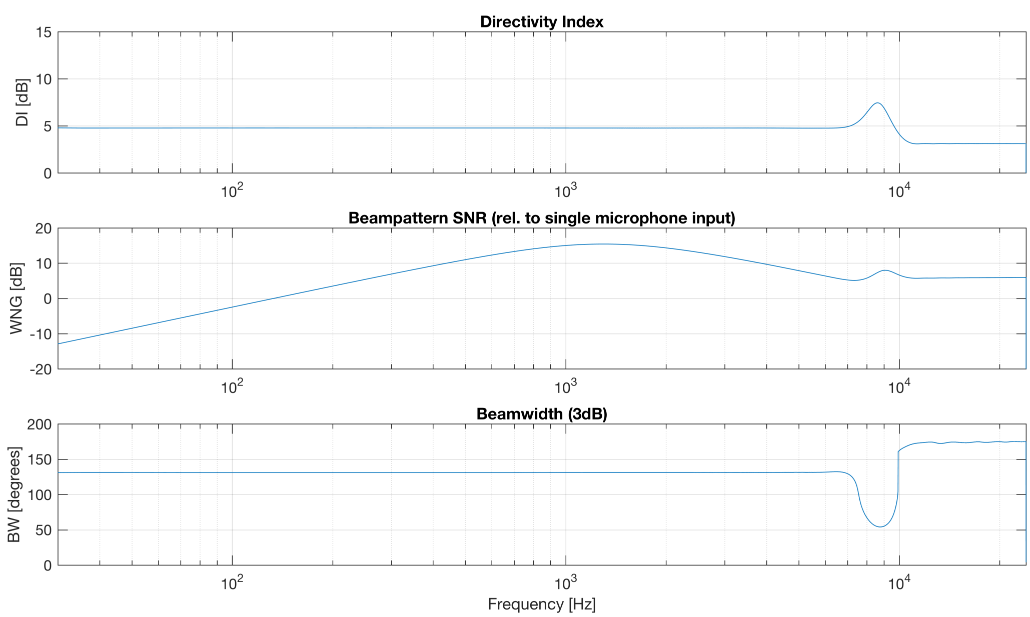
1st-order Cardioid



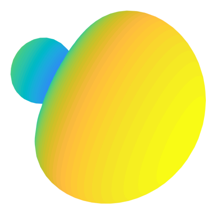


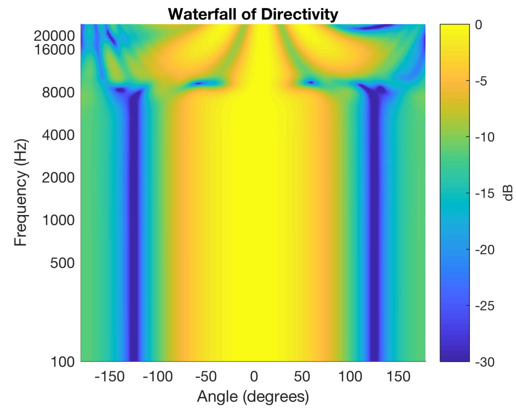


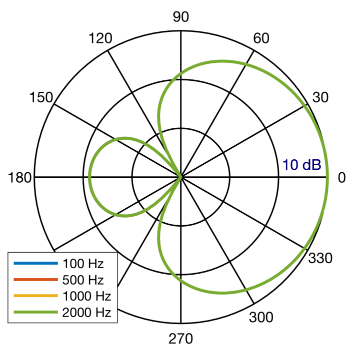


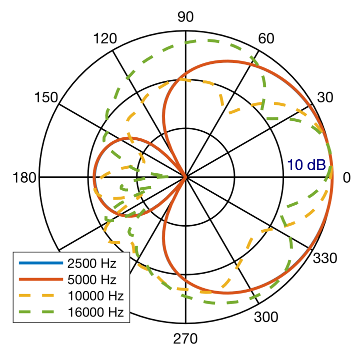


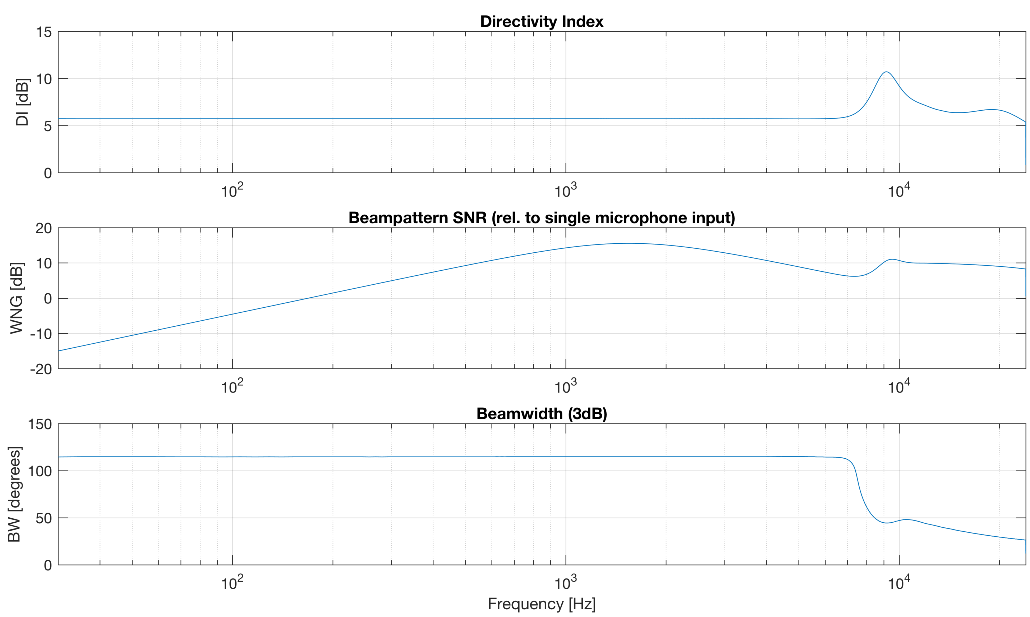
1st-order Supercardioid



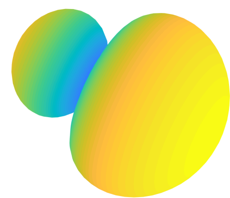


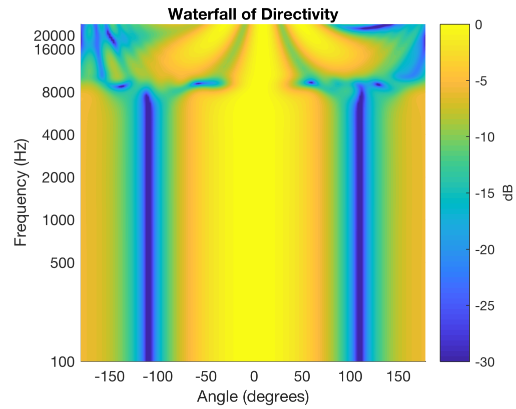


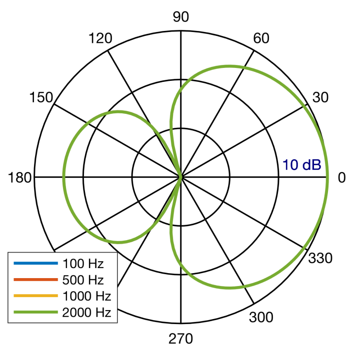


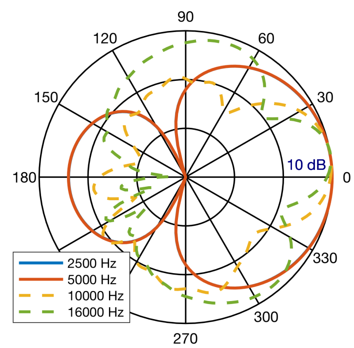


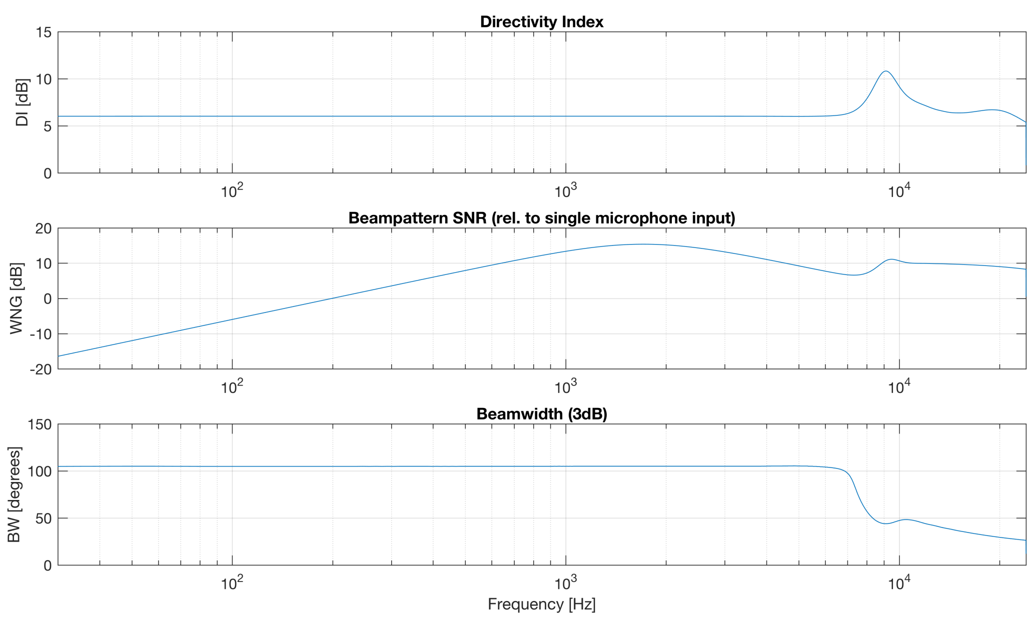
1st-order Hypercardioid



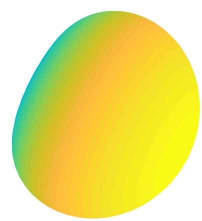


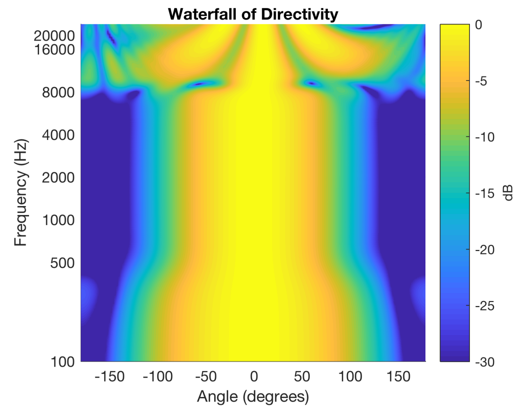


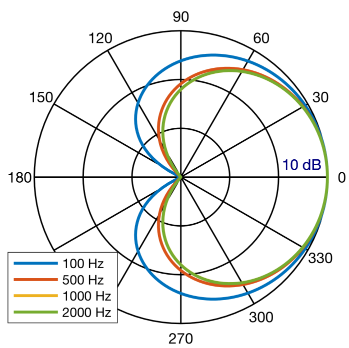


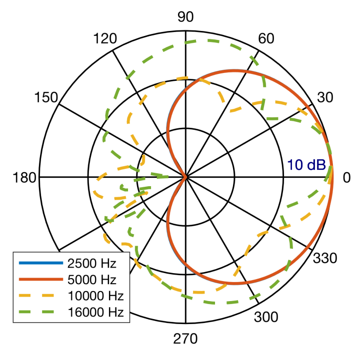


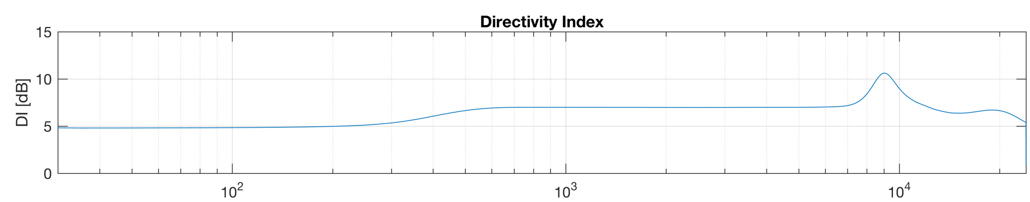
2nd-order Cardioid

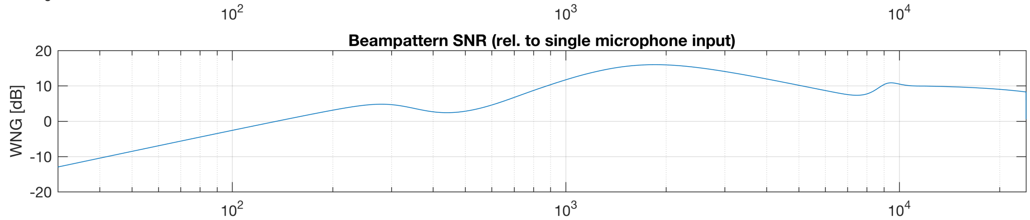


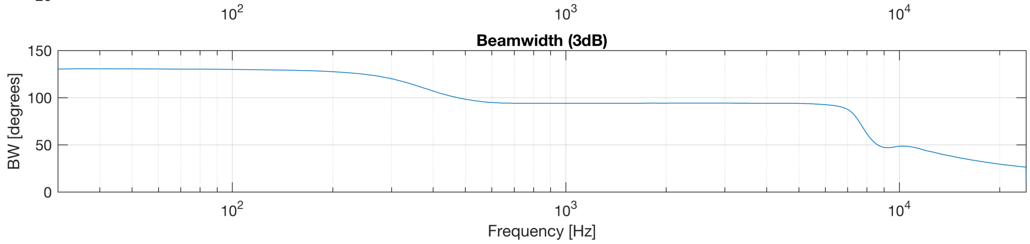




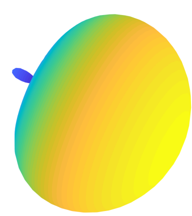


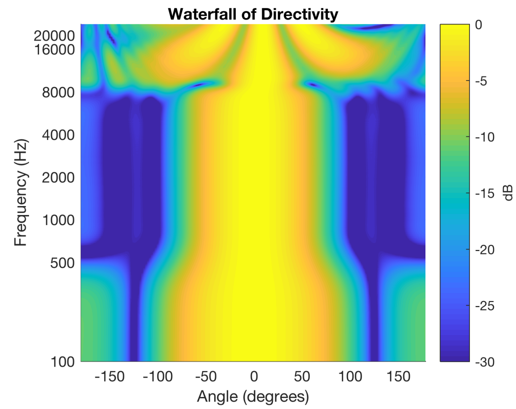


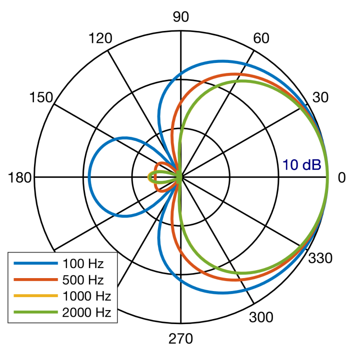


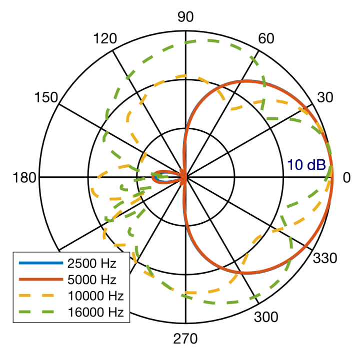


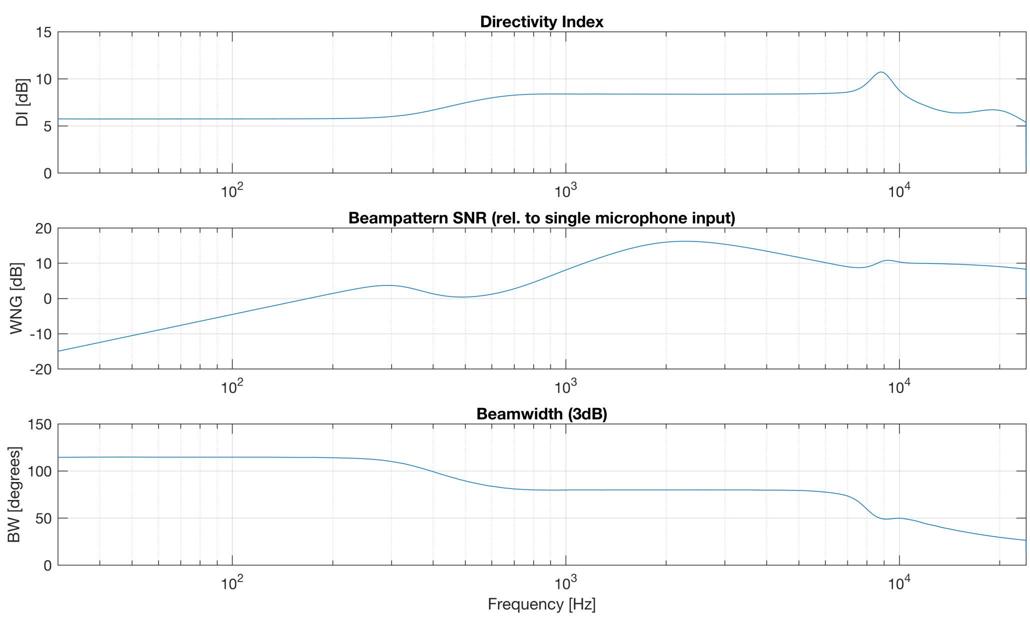
2nd-order Supercardioid



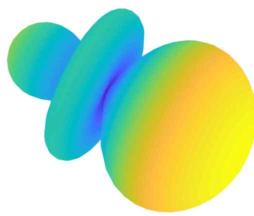


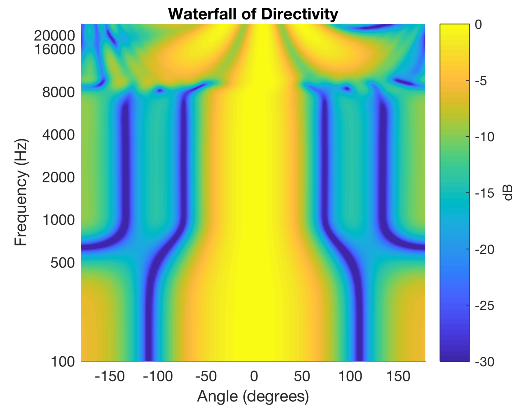


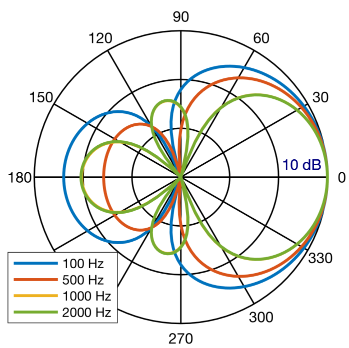


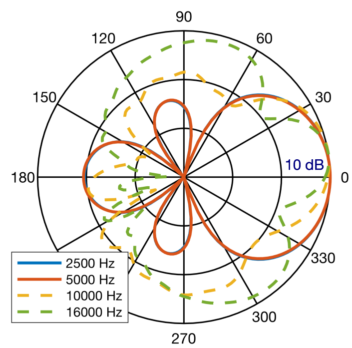


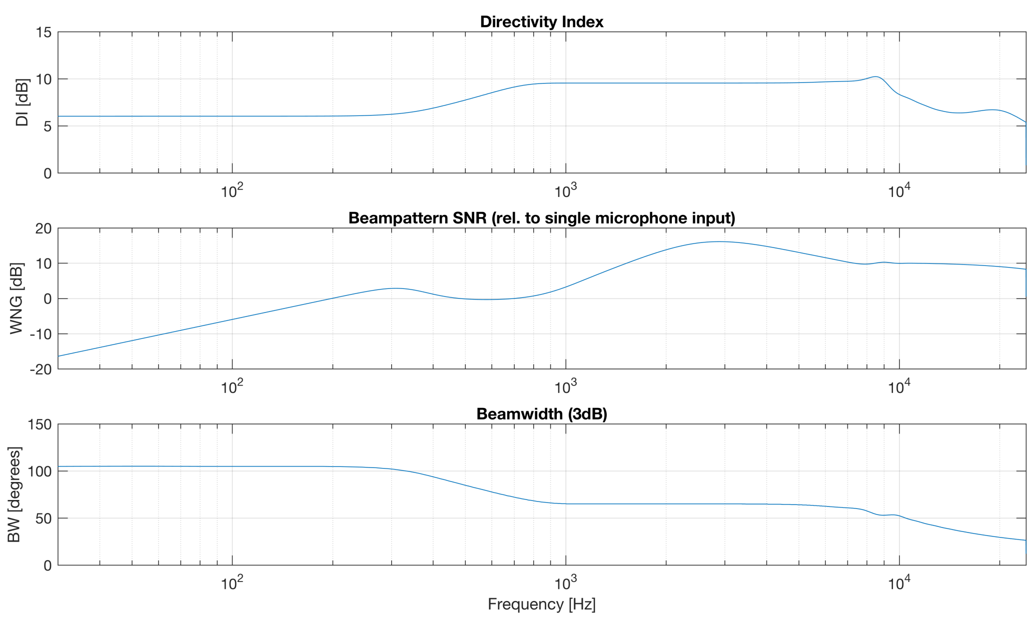
2nd-order Hypercardioid



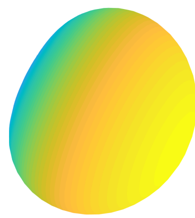


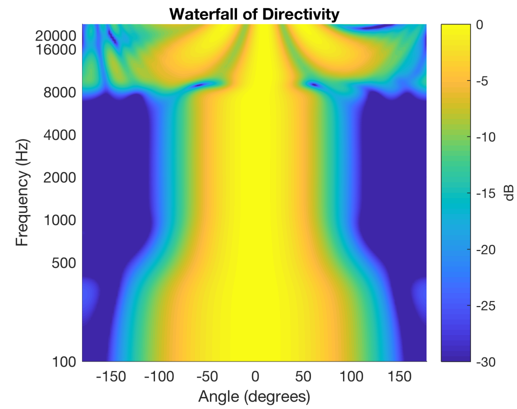


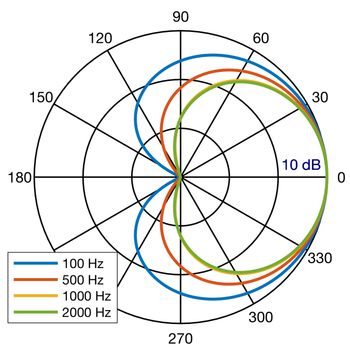


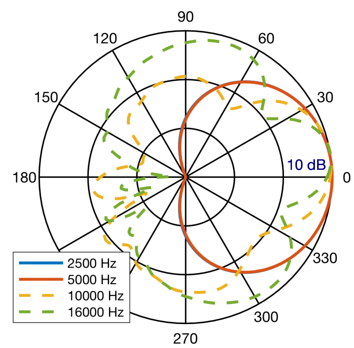


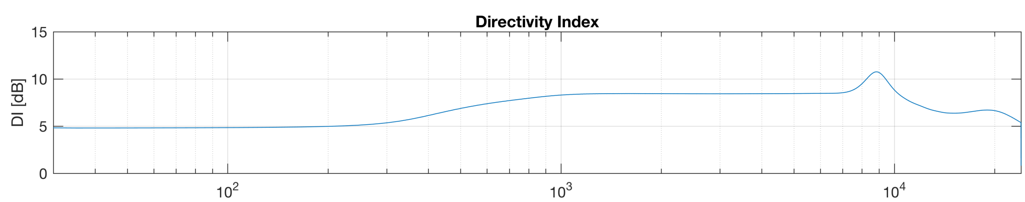
3rd-order Cardioid

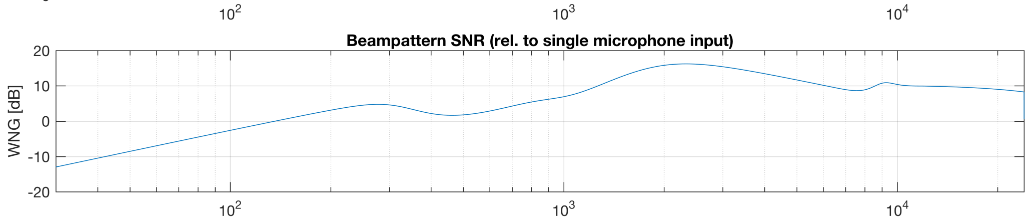


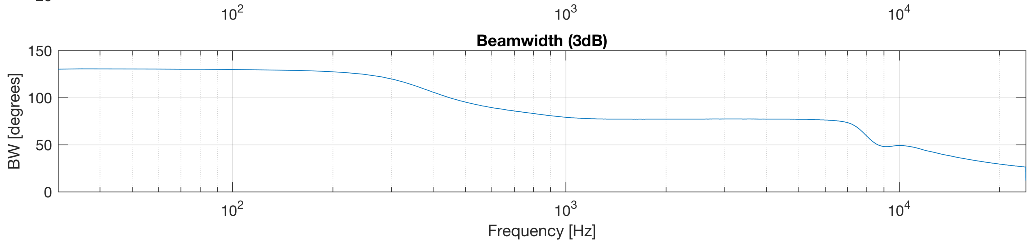




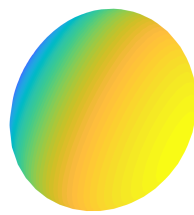


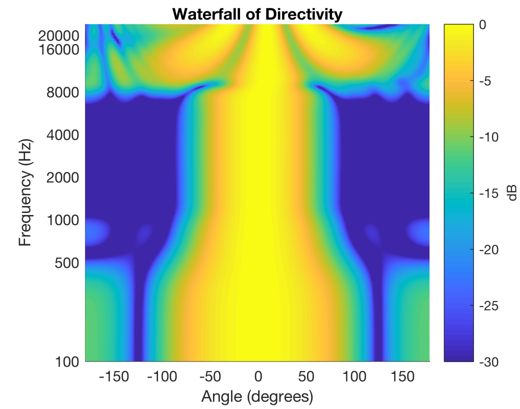


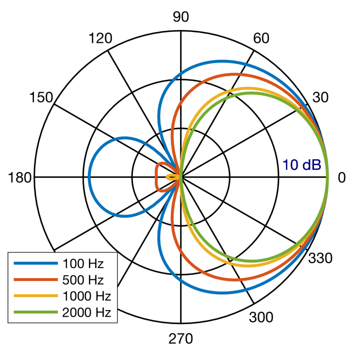


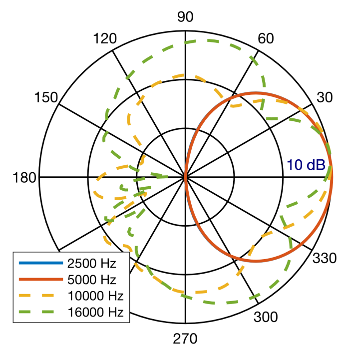


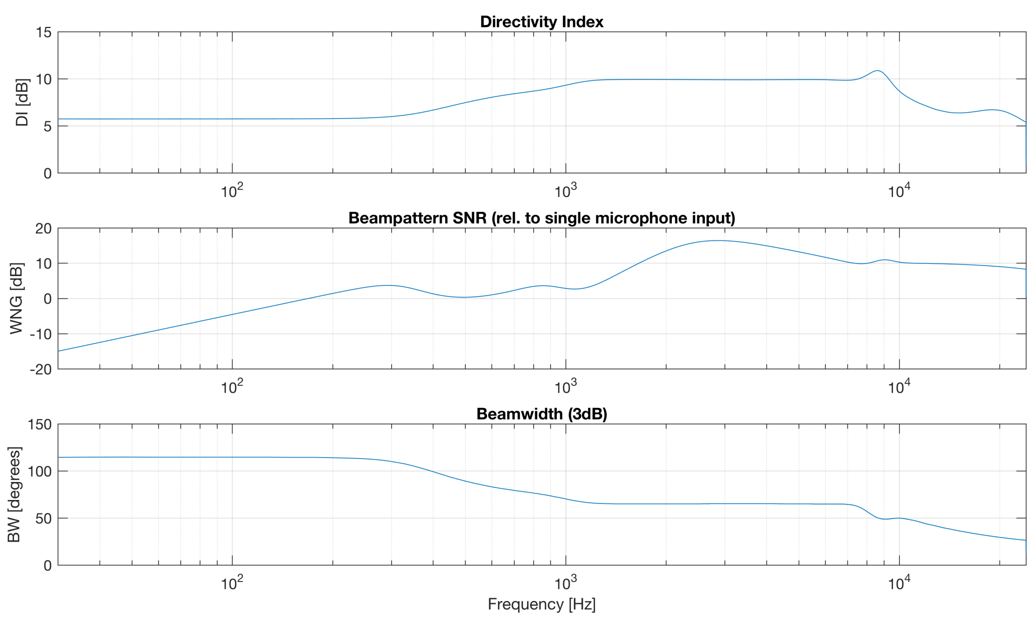
3rd-order Supercardioid



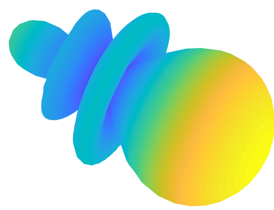


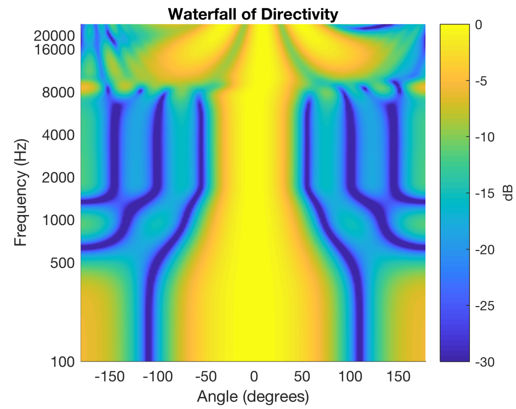


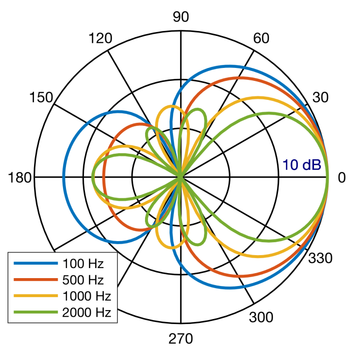


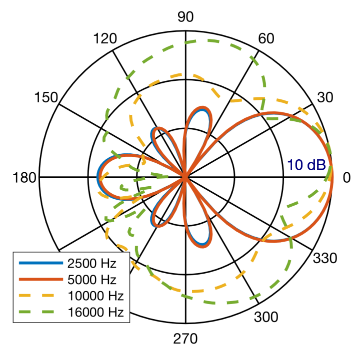


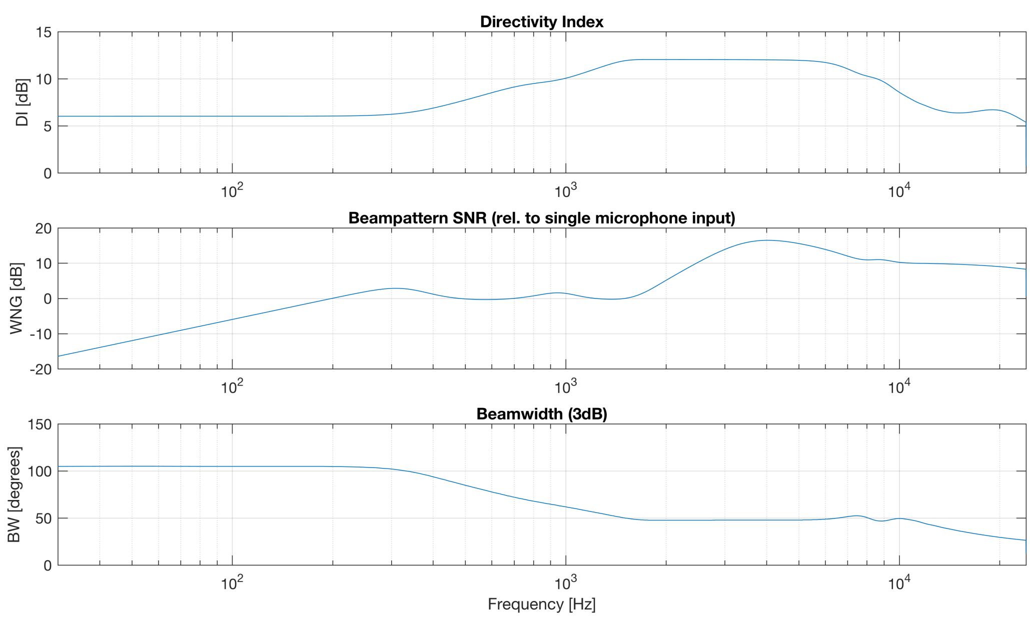
3rd-order Hypercardioid



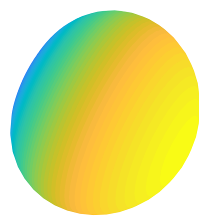


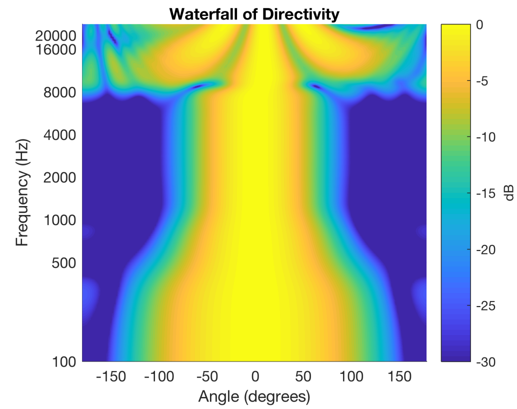


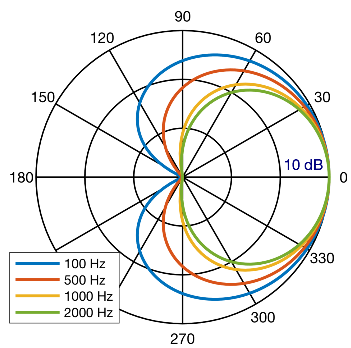


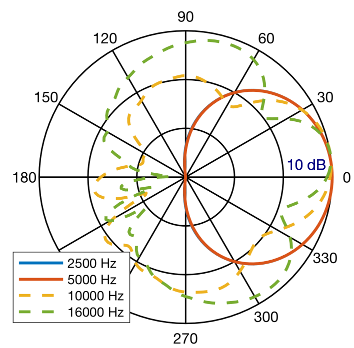


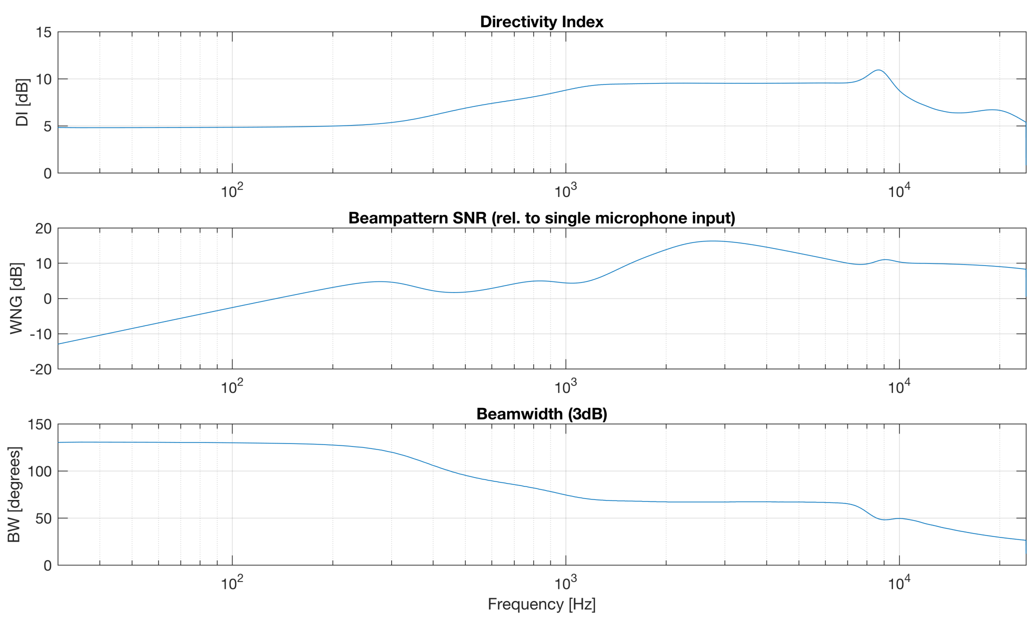
4th-order Cardioid



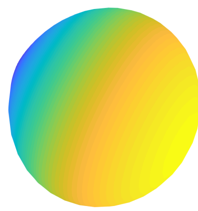


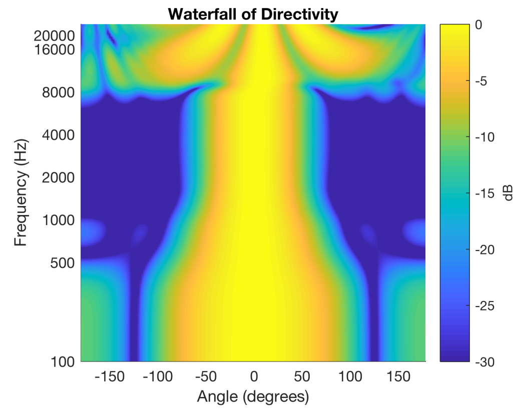


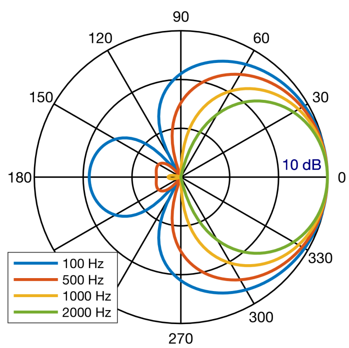


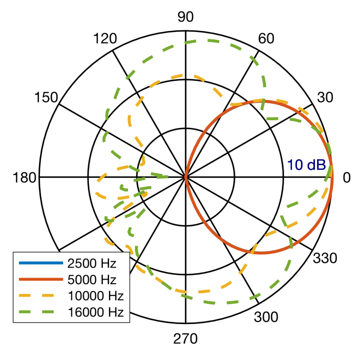


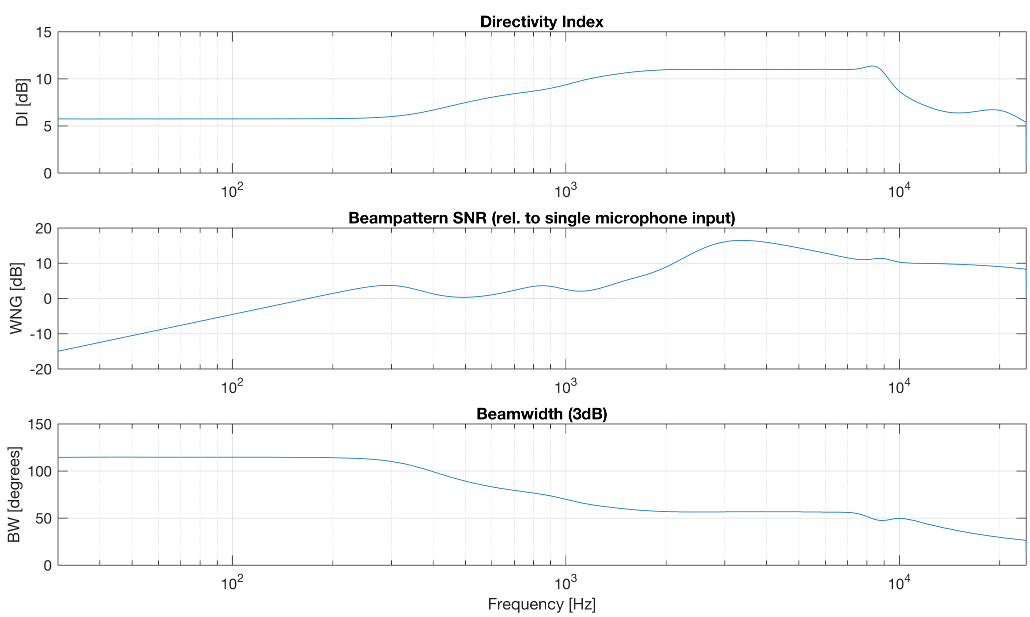
4th-order Supercardioid











4th-order Hypercardioid