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Directivity and Electro-Acoustic Measurements of the IKO

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ABSTRACT

The icosahedral loudspeaker (IKO) as a compact spherical array is capable of 3rd order Ambisonics (TOA) beamforming, and it is used as musical and technical instrument. To develop and verify beamforming with its 20 loudspeakers flush-mounted into the faces of the regular icosahedron, electro-acoustic properties must be measured. We offer a collection of measurement data of IEM's IKO1, IKO2 and IKO3 along with analysis tools to inspect these properties. Multiple-input-multiple-output (MIMO) data comprises: (i) laser vibrometry measurements of the 20x20 transfer functions from driving voltages to loudspeaker velocities, (ii) 20x16 finite impulse responses (FIR) of the TOA decoding filters, and (iii) 648x20 directional impulse responses from driving voltages to radiated sound pressure. With the open data sets, open source code, and resulting directivity patterns, we intend to support reproducible research about beamforming with spherical loudspeaker arrays.

1 Introduction

Compact spherical loudspeaker arrays are capable of grating-lobe free beamforming into all directions, with rotation-invariant beam patterns over several octaves. They are used as technical and musical instruments, such as for (room) acoustic measurement, home entertainment, media installations and computer music. The latter introduced a convenient approach for composing sonic sculptures, also called plastic sound objects [1] by IKO's sound beams exciting room reflections [2].

The regular icosahedral cabinet with 20 faces and 20 individually controlled 6-inch full-band drivers is a good compromise for numerical robust TOA based beamforming utilizing 16 spherical eigenmodes. It provides sufficient low-frequency performance and a reasonably high spatial aliasing frequency, thus exciting the whole audio bandwidth with proper beam control between approximately 100 Hz and 1 kHz [2].

A first prototype IKO1 was built at IEM in 2006, using an edge length 0.345 m and initially 6.5", later 6" drivers, cf. IKO history¹. To promote technical and artistic research and based on the idea of improved mobility and compactness, the prototypes IKO2 and IKO3—manufactured by the Graz based company sonible utilizing 6" drivers—were acquired in 2016 and 2018 within the scope of the dedicated *IKO* by *IEM* and *sonible* cooperation². Compared to IKO1, the newer prototypes IKO2 and IKO3 exhibit more powerful and technically improved transducers along with a smaller cabinet size. IKO3 is slightly larger than IKO2 as a consequence of an improved manufacturing process (edge lengths: 0.288 m for IKO2 vs. 0.294 m for IKO3). IKO1 was utilized in the studies [1, 2] and IKO2 was deployed for [3, 4].

¹<https://iem.kug.ac.at/projects/osil/about-the-iko.html>

²<https://iko.sonible.com>

2 Open Source Data and Software

To research, develop, improve, and validate beamforming, electro-acoustic properties were measured for IKO1,2,3. These measurements are continuously updated on our open access digital repositories located at Phaidra³. The present engineering brief accompanies the effort to collect directivity dedicated measurements and derived data within a consistent framework and to provide analyzing tools. For ongoing research at IEM, cf. [5, 6], the dedicated open data webpage⁴ contains documentation, Phaidra links of the data and analyzing software. For each IKO the SOFA⁵ formatted data

- 20x20 transfer impulse responses from driving voltages to loudspeaker velocities using laser vibrometry
- 20x16 FIR TOA decoding filters derived from the velocity measurements
- 648x20 (IKO1,2) and 540x20 (IKO3) directional impulse responses from loudspeaker driving voltage to calibrated microphone receiving voltages

are available at the Phaidra link⁶. For analyzing IKO beamforming the open source tool *balloon_holo* is provided, cf. Fig. 1. The software is capable of loading the SOFA data and of interactively inspecting balloon, polar and surface directivity plots. Furthermore, the TOA decoding FIR filters and configuration files are provided for DAW support with the *mcfx_convolver* plugin⁷ and the *ambix_encoder_o3* plugin⁸.

2.1 Velocity Measurements

The impulse response of each loudspeaker cone's center was measured with a Polytec PDV-100 laser vibrometer. All loudspeakers act on a common volume, which couples their vibrations. Thus, a matrix of 20x20 crosstalk impulse responses, whose diagonal entries contain the active paths, was acquired to design TOA decoding filters including velocity equalization and active crosstalk cancellation. Fig. 2 exemplarily shows the transfer functions of the 20 IKO2 loudspeakers for one loudspeaker actively driven by an input signal.

³<https://phaidra.kug.ac.at>

⁴<https://opendata.iem.at>

⁵<https://www.sofaconventions.org>

⁶https://phaidra.kug.ac.at/detail_object/o:67609

⁷<https://github.com/kronihias/mcfx>

⁸<https://github.com/kronihias/ambix>

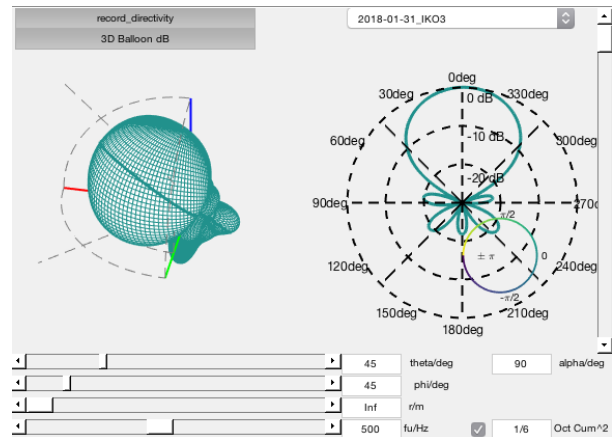


Fig. 1: Matlab based GUI of *balloon_holo* as analyzing tool for IKO beamforming.

2.2 Ambisonic Decoding Filters

A suitable filter design for a max- r_E -weighted TOA decoding is discussed in [2], which uses modal gain limitation of the loudspeaker cone excursions (ranging from 0th order for LF to 3rd for HF). Instead of the trace of crosstalk matrix as in [2, p.63, right col], the filter design here uses a transfer function of a suitable electro-mechanical model as a -10 dB attenuated diagonal load for regularization. This is done to increase the robustness in the frequency range around 1.6 kHz, where the velocities exhibit pronounced notch whose full equalization might not always be useful, cf. Fig. 2. The filter design yields a 20x16 FIR matrix with 320 filter-and-sum operations of 4096 taps. The partitioned block convolution of the *mcfx_convolver* offers an efficient rendering thereof. Its efficiency relies on gathered

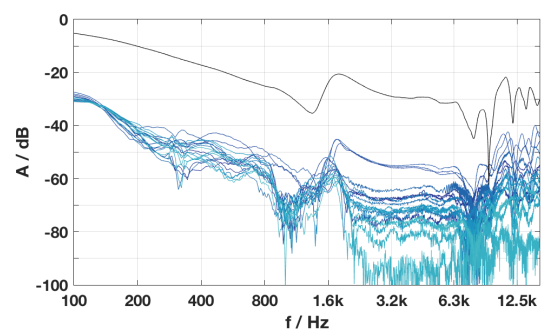


Fig. 2: Typical voltage to velocity transfer functions of IKO2 derived by laser vibrometry. Black...active loudspeaker, blue...passive loudspeakers.

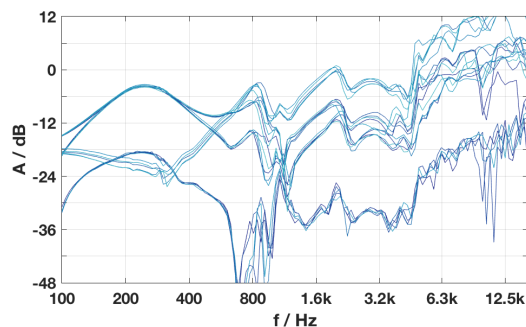


Fig. 3: Typical driving filters of the 20 IKO1 loudspeakers for beam steering to a vertex.

FFTs at the 16 inputs and IFFTs at the 20 outputs, instead of individual FFT-IFFT pairs for each of the 320 paths. Fig. 3 shows exemplary magnitude responses of the TOA decoding filters for a beam to an IKO1 vertex.

2.3 Sound Pressure Measurements

To analyze radiation characteristics, the IKOs were set up in a surrounding microphone array in a measurement chamber. Then directional impulse response from every loudspeaker to every microphone was measured by interleaved exponential sweeps. For IKO1 and IKO2, directional responses were obtained on an equiangular grid of 18×36 zenith and azimuth angles (648 points, spherical harmonics transform (SHT) order ≤ 17). For IKO3 the equiangular grid used 15×36 positions in zenith and azimuth (540 points, SHT order ≤ 14). Based on exterior SHT domain wave field extrapolation, the directional response is obtained in the far field. To involve the IKO's beam control, the input of the 20 directional far-field responses are convolved with the TOA decoding filters for a desired beam direction.

3 Results

The figures here are based on the following data sets: IKO1: LV 12/2015, FIR 03/2018, MIC 08/2011
IKO2: LV 08/2017, FIR 03/2018, MIC 06/2016
IKO3: LV 01/2018, FIR 03/2018, MIC 01/2018 (LV...laser vibrometer measurement, FIR...TOA decoding filters, MIC...mic array measurement)

Directivity patterns in Fig. 4 for IKO1,2,3, and balloons for IKO3 in Fig. 5 were rendered using *balloon_holo*, cf. Fig. 1. Fig. 4 illustrates the slightly lower operational frequency range of the beams of IKO1 vs. those of IKO2,3 due to its 20% larger cabinet size.

Main lobe differences of IKO3 to IKO2 due to its 1% larger cabinet size are negligible. Except for the expected kr -dependency, the velocity measurements, the filter transfer functions, and the resulting radiation patterns show similar characteristics.

Face beam denotes a beam directed on-axis with an IKO loudspeaker/facet, *edge beam* denotes a beam directed through the middle of an IKO edge, where two facets meet, while *vertex beam* denotes a beam directed through an IKO corner, where five facets meet. Patterns of these directions exhibit characteristic grating lobes as shown in the middle and bottom row of Fig. 5. A face beam produces prominent grating lobes at adjacent vertices. For edge and vertex beams prominent grating lobes occur in face direction. A vertex beam is somewhat super-directive due to the constructive interference of the five adjacent in-phase loudspeakers.

4 Summary

This contribution briefly discussed the efforts of collecting and analyzing open source data and software for the TOA beamformer IKO.

For research on (spherical) acoustic arrays at the IEM, the dedicated open data webpage <https://opendata.iem.at> linking to the repository <https://git.iem.at/groups/opendata> serves as reference to access all software, documentation, and Phaidra links to SOFA formatted data.

References

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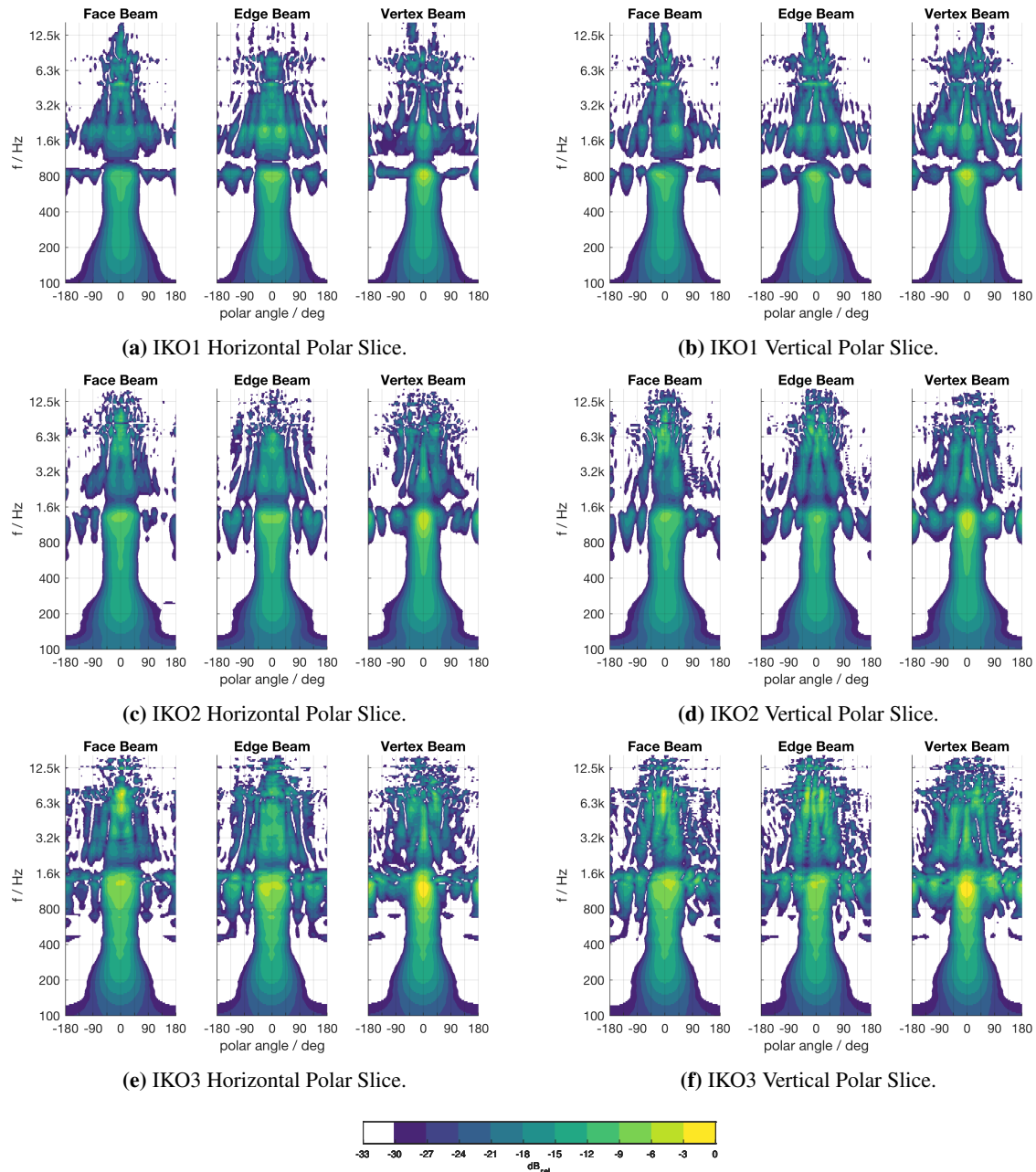


Fig. 4: Horizontal and vertical directivity patterns for IKO1,2,3 using Ambisonic beamforming with frequency dependent order (cf. [2, Fig. 13]) and max \mathbf{r}_E -weighting. Colorbar indicates viridis colormap with 3 dB per color. Normalization for each subplot to a value derived from (i) energy in band 100 Hz to 400 Hz and (ii) averaging case (i) for $\pm 10^\circ$ along the main lobe. Overall normalization such that just no colormap clipping. Edge lengths: 0.345 m IKO1, 0.288 m IKO2, 0.294 m IKO3.

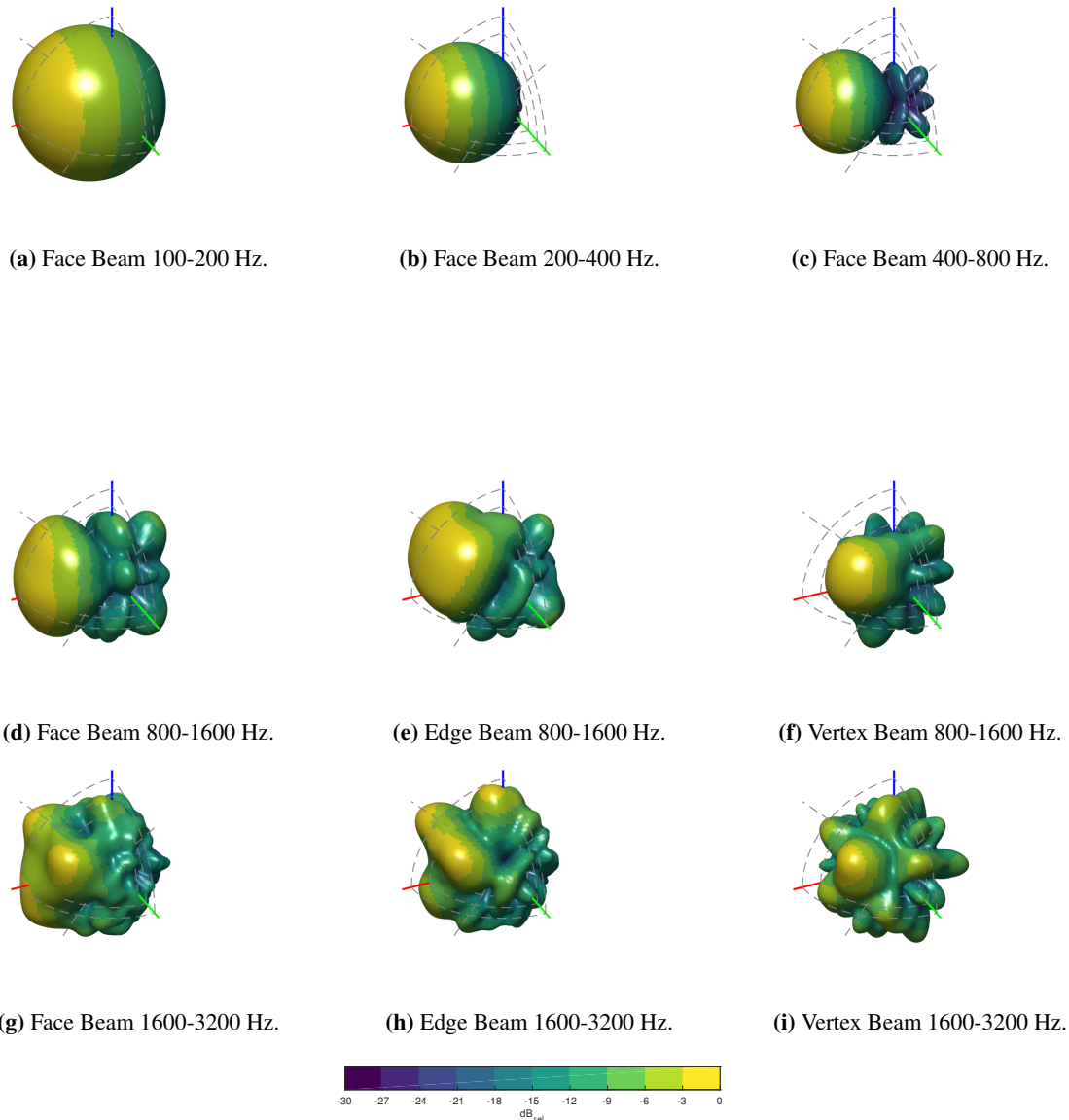


Fig. 5: Directivity balloon characteristic for IKO3 using Ambisonic beamforming with frequency dependent order (cf. [2, Fig. 13]) and max r_E -weighting. Colorbar indicates viridis colormap with 3 dB per color and 30 dB resolution. 3D polar diagram grid use 6 dB/div. The balloon radius and the color indicate dB-values of energy per frequency band defined by the given lower and upper cut frequency. Each subplot normalized to balloon's maximum dB value. Top row: up to about 1 kHz main lobe patterns are independent of the beam direction, exemplarily shown for a face beam here. Middle and bottom row: above 1 kHz frequency-dependent grating lobes arise that yield characteristic patterns for beams into face (left column), edge (center column) and vertex (right column) direction of the icosahedral shaped loudspeaker cabinet.