Soundfield Microphones: Design and Calibration
soundfield microphones

• the goal:
  - we have a number of microphone capsules arranged in space
  - they feed a “black box” that does some processing
  - the output of which is the ambisonics components of the soundfield the capsules are immersed in
soundfield microphones

- the building blocks:
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- the building blocks:
  - microphone capsules
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- the building blocks:
  - microphone capsules
  - two types:
soundfield microphones

- the building blocks:
  - microphone capsules
  - two types:
    - omnidirectional (closed diaphragm, pressure)
    - figure of eight (open diaphragm, velocity)
soundfield microphones

• the building blocks:
  - microphone capsules
  - two types:
    • omnidirectional (closed diaphragm)
    • figure of eight (open diaphragm)
  - or a linear combination of the above:
    • cardioid (partially open back of diaphragm)
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- the building blocks:
  - omnidirectional
    - much easier to build
    - low frequency down to earthquakes if you want
    - lower noise
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- the building blocks:
  - cardioid (partially open back of diafragm)
    - much more difficult to build
    - captures velocity instead of pressure
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- the building blocks:
  - microphone capsules
- spatial arrangement of capsules
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- the building blocks:
  - microphone capsules
- spatial arrangement of capsules
  - to sample the sphere uniformly
    - use platonic solids
    - use other equal spacing schemes (t-designs, etc)
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• the building blocks:
  ¬ platonic solids

<table>
<thead>
<tr>
<th>Polyhedron</th>
<th>Vertices</th>
<th>Edges</th>
<th>Faces</th>
<th>Schläfi symbol</th>
<th>Vertex configuration</th>
</tr>
</thead>
<tbody>
<tr>
<td>tetrahedron</td>
<td>4</td>
<td>6</td>
<td>4</td>
<td>{3, 3}</td>
<td>3.3.3</td>
</tr>
<tr>
<td>cube</td>
<td>8</td>
<td>12</td>
<td>6</td>
<td>{4, 3}</td>
<td>4.4.4</td>
</tr>
<tr>
<td>octahedron</td>
<td>6</td>
<td>12</td>
<td>8</td>
<td>{3, 4}</td>
<td>3.3.3.3</td>
</tr>
<tr>
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<td>20</td>
<td>30</td>
<td>12</td>
<td>{5, 3}</td>
<td>5.5.5</td>
</tr>
<tr>
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<td>12</td>
<td>30</td>
<td>20</td>
<td>{3, 5}</td>
<td>3.3.3.3.3</td>
</tr>
</tbody>
</table>
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- number of capsules determines
  - order of spherical harmonics that can be sampled without aliasing
soundfield microphones

- number of capsules determines
  - order of spherical harmonics that can be sampled without aliasing
- spatial arrangement
  - uniform for optimal sampling with minimal error
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• how do we arrange the capsules?

first approach:

• uniform spacing on the surface of an open sphere
• using pressure microphones (omni)
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\[ p(k, r', \theta', \phi') \approx \sum_{n=0}^{N} \sum_{m=-n}^{n} \frac{j_n(kr')}{j_n(kr)} p_{nm}(k, r) Y_n^m(\theta', \phi'). \]

from “Fundamentals of Spherical Array Processing”, Rafaely (Springer) (eq 4.2, or derivation that leads to 2.48)
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\[ p(k, r', \theta', \phi') \approx \sum_{n=0}^{N} \sum_{m=-n}^{n} \frac{j_n(kr')}{j_n(kr)} p_{nm}(k, r) Y_n^m(\theta', \phi'). \]

(pressure somewhere based on pressure somewhere else)
soundfield microphones

\[ p(k, r', \theta', \phi') \approx \sum_{n=0}^{N} \sum_{m=-n}^{n} \frac{j_n(kr')}{j_n(kr)} p_{nm}(k, r) Y_n^m(\theta', \phi'). \]
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- open sphere, omni capsules
  - zeroes in Bessel functions determine frequencies at which we cannot really calculate the sampling
  - decrease of functions towards the origin places a limit on the low frequency response of the array
  - spatial aliasing determines the upper working frequency limit

(also, might be difficult to build...)
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- rigid sphere, omni capsules
  - incident field + scattered field
  - no nulls in denominator
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- rigid sphere, omni capsules
  - incident field + scattered field
  - no nulls in denominator
  - easier to build (there is a 32 capsule rigid sphere array at ccrma!)
  - tradeoff: we need a large sphere for low frequency operation but that is not desirable for other reasons
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- rigid sphere, omni capsules:
  eigenmike (32 capsules)
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- rigid sphere, omni capsules:
  zylia (19 capsules)
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- open sphere, cardioid capsules
  - again, no nulls
  - 1\textsuperscript{st} order: no low frequency drop
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- open sphere, cardioid capsules
  - again, no nulls
  - even better low frequency performance (theory)
  - but: inherent higher noise at low frequencies
  - but: deviation from cardioid pattern will affect sampling accuracy
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- open sphere, cardioid capsules (1\textsuperscript{st} order)
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• open sphere, cardioid capsules (partial 2\textsuperscript{nd} order)
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- multiple open spheres, omni capsules
  - nulls for one sphere do not happen for the other
  - just imagine building one...

(might be the only solution for extended frequency range capture of higher order components...)

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- spherical arrays are not the only topology being explored
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- spherical arrays are not the only topology being explored
  - “Acoustically hard 2D arrays for 3D HOA”, Svein Berge, 2019
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- spherical arrays are not the only topology being explored
  - “Acoustically hard 2D arrays for 3D HOA”, Svein Berge, 2019
  - pressure-sensitive sensors on both sides of an acoustically hard plate (solid state MEMS capsules)
  - multiple radius array!
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• “Acoustically hard 2D arrays for 3D HOA”, Svein Berge, 2019
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- “Acoustically hard 2D arrays for 3D HOA”, Svein Berge, 2019
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- back to first order Ambisonics microphones
  - created in the ‘70s by Gerzon
  - open sphere with cardioid capsules
  - tetrahedral configuration
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• first order Ambisonics microphones
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• first order Ambisonics microphones
  - how do you calibrate them?
    (why do you calibrate them?)
  • there are plenty of papers but manufacturers do not tell you what they do (in detail)

“The Design of Precisely Coincident Microphone Arrays for Stereo and Surround Sound”, Gerzon, 1975

- how to make them?
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- end of 2014, start of the SpHEAR project
  (Spherical Harmonics Ear)
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• goals:
  – 3d printed Ambisonics microphone
    • printable on “cheap” 3d printers (what we have)
    • precise and repeatable mechanical design
  – interface electronics, PCB (printed circuit board) design and fabrication
  – calibration: measurements and software
    • automatic calibration with (almost) no manual intervention
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• goals:
  - everything accessible and open (GPL + Creative Commons)
  - design and build using only Free Software components
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• goals:
  - students in Music222 should be able to build their own microphones!
soundfield microphones

• goals:
  – students in Music222 should be able to build their own microphones!
  – how hard can it be?
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• goals:
  - students in Music222 should be able to build their own microphones!
  - how hard can it be?
    (turns out it is pretty hard...)
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• mechanical design:
  – models written in OpenScad, free software language based 3d modeling software
  – using Cura as the slicer
  – printing on an Ultimaker 3d printer (filament extrusion printer)
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• mechanical design:
  - start from a classical 4 capsule tetrahedral design – print capsule holders flat, then assemble as in a 3d puzzle
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- mechanical design:
  - start from a classical 4 capsule tetrahedral design – print capsule holders flat, then assemble as in a 3d puzzle
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- mechanical design:
  - this same concept can be scaled up to more capsules (Octathingy by Eric Benjamin)
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• mechanical design:
  – or, of course, to other platonic solid designs
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- mechanical design:
  - or, of course, to other platonic solid designs
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- mechanical design:
  - the first prototype was very simple but functional
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- electronic design:
  - the first prototype used a very simple interface, one capacitor and one resistor (fits into the shell of an XLR connector!
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- electronic design:
  - the first prototype used a very simple interface, one capacitor and one resistor (fits into the shell of an XLR connector!
    - not balanced
    - any phantom power supply noise leaks into the signal -> very bad low frequency noise performance
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• electronic design:
  - the proper design has to be balanced and supply the proper current to the capsule
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- electronic design:
  - the proper design should be balanced and supply the proper current to the capsule
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- electronic design (Kicad):
  - a much simpler version of this was selected (the zapnspark variant)
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- electronic design (Kicad):
  - a much simple version of this was selected (the zapnspark variant)
  - a PCB was designed and built
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- mechanical design:
  - a full microphone houses four PCBs and the capsule array (and a 12 pin DIN connector)
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- calibration (Heller, 2007, unpublished)

  one capsule:

  \[ T_F = T_{F_0} \cdot (1 + \cos \vartheta) \]

  response is pressure plus velocity vector

  \[ R(x) = p + x \cdot v, \]
• calibration (Heller, 2007, unpublished)

in matrix notation:

\[ R = \begin{bmatrix} 1 & x_x & x_y & x_z \end{bmatrix} \begin{bmatrix} p & v_x & v_y & v_z \end{bmatrix}^T \]

we have four unknowns, so we need at least four measurements (more is better, equally spaced is better)
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- calibration (Heller, 2007, unpublished)

  our measurements can be expressed as:

  \[ R = \begin{bmatrix} r_1 & \ldots & r_i & \ldots & r_n \end{bmatrix}^T, \]

  and the directions of the measurements is:

  \[ X = \begin{bmatrix} 1 & x_{1x} & x_{1y} & x_{1z} \\ \vdots & \vdots & \vdots & \vdots \\ 1 & x_{nx} & x_{ny} & x_{nz} \end{bmatrix}, \]
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• calibration (Heller, 2007, unpublished)

finally our unknowns:

\[
M = \begin{bmatrix} p & v_x & v_y & v_z \end{bmatrix}^T
\]

in matrix form:

\[
R = XM.
\]
\[
M = X \backslash R.
\]
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- calibration (Heller, 2007, unpublished)

so, we need to invert our measurement matrix, multiply by the measurement directions and we obtain our unknowns (pressure and velocity vector)

\[ M = X \backslash R. \]
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- measurements, we need:
  - anechoic chamber (we do not have one)
  - calibrated reference microphone
  - single driver full range speaker
  - software:
    - impulse response measurement system (aliki)
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• measurements
  - we measure 16 impulse responses, equally spaced around the microphone (in the horizontal plane only for simplicity)
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• measurements
  - we measure 16 impulse responses, equally spaced around the microphone (in the horizontal plane only for simplicity)
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• measurements:
  - anechoic chamber
  • stage – truncate response up to first reflection
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- measurements:
  - stage – truncate response up to first reflection
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- measurements:
  - process reference microphone IR through DRC, we get a calibration filter
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• measurements:
  - process all measurements through the calibration filter and get calibrated IRs
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• calibration:
  – finally, we have 16 x 4 calibrated impulse responses and we can read them into the R matrix
  – load them, select a frequency range for the measurement, measure average power, create R matrix
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- calibration:
  - first check that the measurements make sense
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- calibration:
  
  our R matrix is (1200-2400Hz):

  octave:26> R
  R =

  8.6777e-03  8.3897e-03  1.3729e-03  1.8104e-03
  1.0270e-02  6.5737e-03  2.8724e-03  6.0254e-04
  1.0931e-02  4.4959e-03  4.6878e-03  4.5029e-04
  1.0635e-02  2.3798e-03  6.8391e-03  4.7192e-04
  9.5783e-03  8.5023e-04  8.6717e-03  1.2031e-03
  7.8287e-03  9.0888e-04  9.9395e-03  2.7618e-03
  5.5557e-03  1.2590e-03  1.0423e-02  4.6166e-03
  3.3196e-03  9.8501e-04  1.0119e-02  6.5521e-03
  1.3707e-03  1.0175e-03  9.0047e-03  8.3059e-03
  4.5652e-04  2.4863e-03  7.1918e-03  9.6371e-03
  8.3075e-04  4.4803e-03  5.1928e-03  1.0204e-02
  6.6883e-04  6.5091e-03  3.1869e-03  9.9829e-03
  4.6598e-04  8.3659e-03  1.5999e-03  8.9923e-03
  2.1404e-03  9.5069e-03  9.1296e-04  7.4267e-03
  4.2097e-03  9.9636e-03  1.0366e-03  5.4693e-03
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• calibration:
  - our A2B matrix is (1200-2400Hz):

```
octave: 28> A2B
A2B =
     0.71284  1.01213  1.02693  1.00245
     0.80923  1.28540 -1.01623 -1.09799
     0.75494 -1.17778  0.99558 -1.08737
     0.74171 -1.04177 -1.10261  1.13505

octave: 29> COND
COND = 1.5376
```
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- calibration:
  
  let's try it, get a BF signal from AF with this matrix
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- calibration:
  - let's try it, get a BF signal from AF with this matrix
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• calibration:
  - let's try it, get a BF signal from AF with this matrix

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• calibration:
  - so we see how the array behaves well up to 3.4KHz and then deviates from theory
  - we can use this calculated response to see what shape a filter should have to try to correct for the problem (Gerzon)
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- calibration:
  - we average some of the measurements to derive our filter shapes
    - principal directions
    - diagonal directions
    - all directions

which option we choose is a design compromise that affects the “sound” of the microphone
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- calibration:
  - average “principal” directions
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• calibration:
  
  - design minimum phase FIR filters based on those shapes

  (we do not have data for Z, but because of symmetry we assume an average of X and Y will do)
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• calibration:
  - now see if it works, ship the AF signals through the A2B matrix and then through the four W, X, Y and Z minimum phase FIR filters
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- calibration:
  - WXY at 0 degrees
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- calibration:
  - WXY at 45 degrees
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- calibration
  - WXY at 90 degrees
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- calibration:
  - another view of the same data
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- calibration:
  - polar patterns (horizontal plane)

600Hz

5KHz

10KHz

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• calibration:
  – the final step is to write a simple Faust program that implements the A2B matrix and the four FIR filters…
  – or transform into a 4x4 matrix compatible with Tetraproc
  – that is our A format to B format encoder (the “black box”
questions?