Forward Operations Security Sensor Network

FOSSN Project Deep Dive

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Project Initiative

Beamforming

Time Direction-of-Arrival Estimation

Array Design

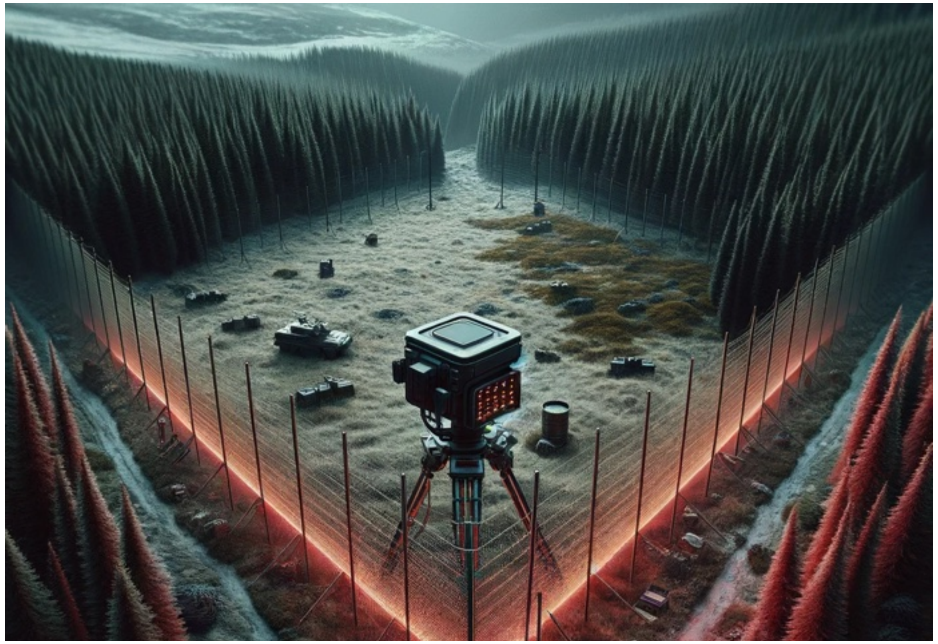
FIR Filters

FOSSN Project Initiative

- intended to address security needs of field artillery units during operations
- operations require concentrated focus and leaves certain areas vulnerable to threats
- FOSSN project is developing a networked sensor system capable of detecting threats autonomously and providing real-time security monitoring without distracting personnel from their primary tasks.

FOSSN Project Goals

- to deploy an unattended network of sensors that automatically detects the presence of encroaching personnel or ground and aerial vehicles
- system will include acoustic, magnetic, and hyperspectral sensors linked through a network
- system that consolidates sensor inputs to alert of any suspicious activity within the monitored area



FOSSN Acoustic Contribution

- What does acoustic sensing bring to the table in a system like this?

- Does not need line of sight:
  - wooded areas
  - night time
  - dusty or foggy environments
  - Low vantage points
- Paired with other sensor, it can increase detection ability

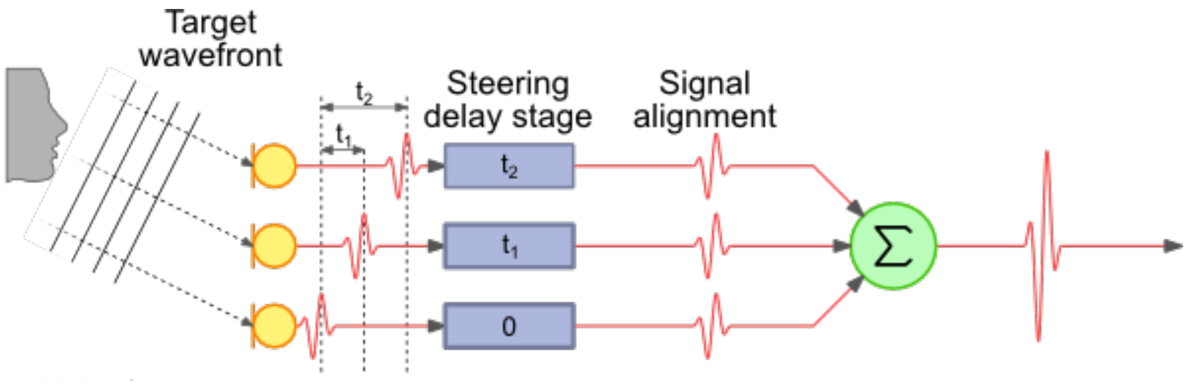
FOSSN Acoustic Objectives

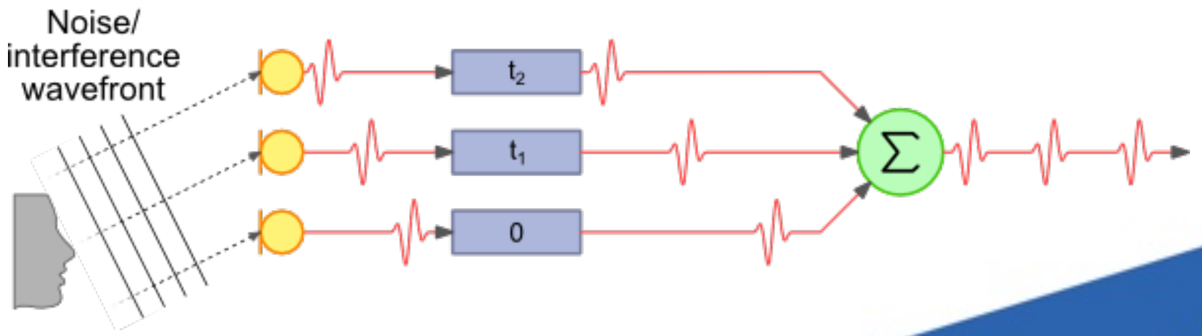
- **Wide Area Coverage:** 180-degree field of view
- **High-Resolution Sensing:** a resolution sufficient to not only detect but also accurately localize targets in conjunction with other sensors
- **Field Demonstrations and Performance Validation:**
  - Conduct field testing to demonstrate the functionality of the acoustic sensors in realistic operational scenarios
  - Determine the effective range and accuracy of the system

Beamforming

- signal processing technique used in sensor arrays for directional signal reception
  - manipulate phases and amplitudes of each signal
  - signals at certain angles experience constructive and destructive interference
- by applying a calculated time delay to each signal, the phases can be aligned at a particular angle of interest

Time = Distance / Rate





Beamforming: Mic Spacing

Time = **Distance** / Rate

- affects how all frequencies respond to the delay and sum processing since each frequency has a different wavelength
- acoustic beamforming must contend with a wide range of frequencies, each with its own wavelength
- microphone spacing that is ideal for one frequency might not be effective for another
- need to find a microphone spacing that works for our targets of interest but is also logistically feasible

Beamforming: Mic Spacing

Time = **Distance** / Rate

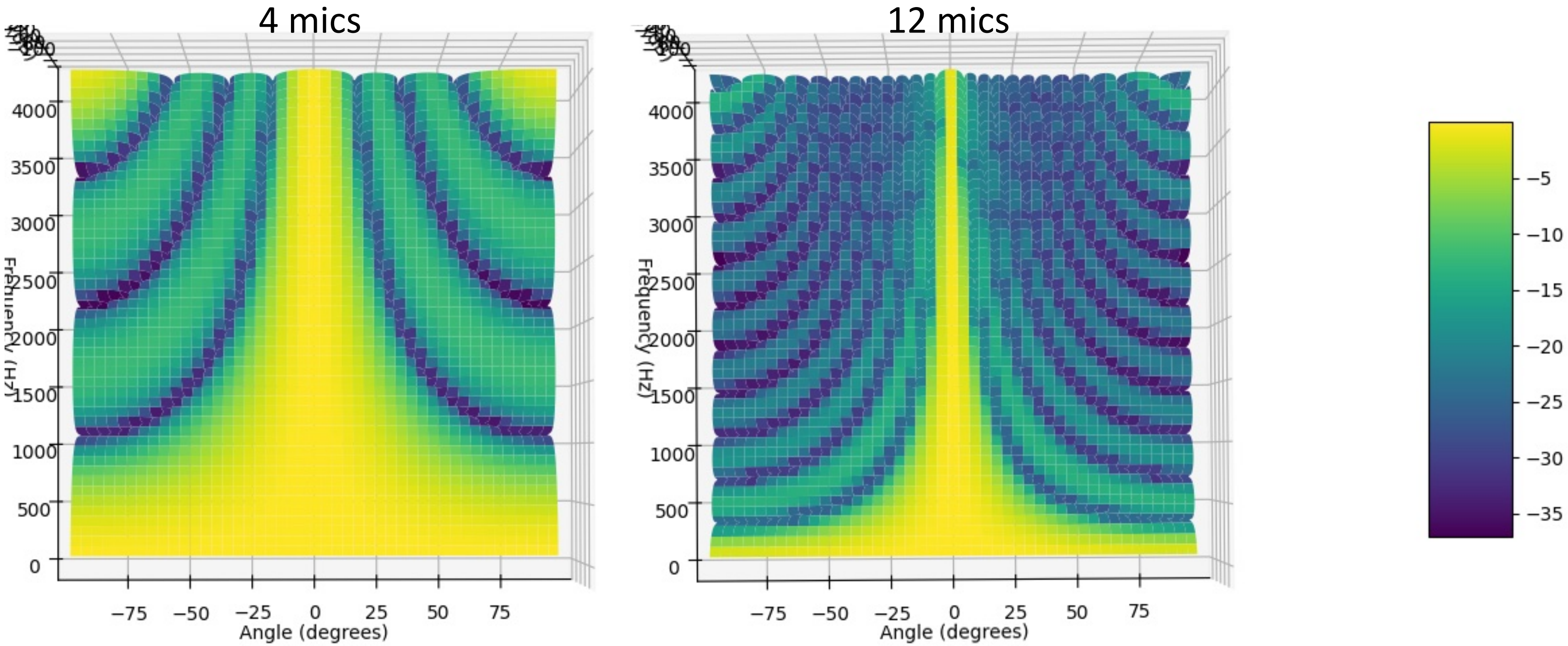
- target range for vehicles is 100 – 400Hz fundamental with harmonics from 500–3000Hz
- center frequency of 1000Hz: mic spacing = 0.17m (6.8in)
  - Using 12 mics across: the array be 6.8ft long
- center frequency of 2000Hz: mic spacing = 0.085 (3.4in)
  - Using 12 mics across: the array be 3.4ft long

- A center frequency closer to 1000Hz would be idea for the targets of interest but spacing for the 2000Hz center makes for a more compact design

Beamforming: Mic Spacing

Time = **Distance** / Rate

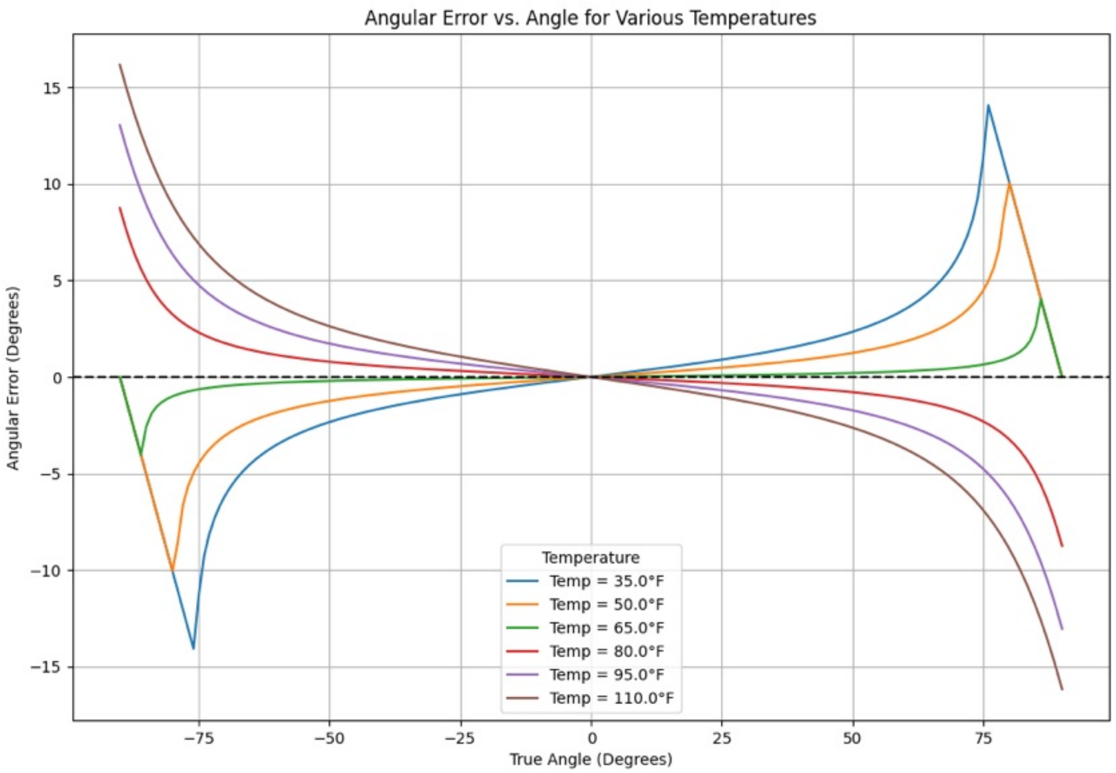
- 12 microphones spaced for 2000Hz center:
  - frequencies down to 400-500Hz have a spatial resolution of ~30 degrees which in combination with higher frequencies with finer resolution should be adequate for this system



Beamforming: Speed of Sound

Time = Distance / **Rate**

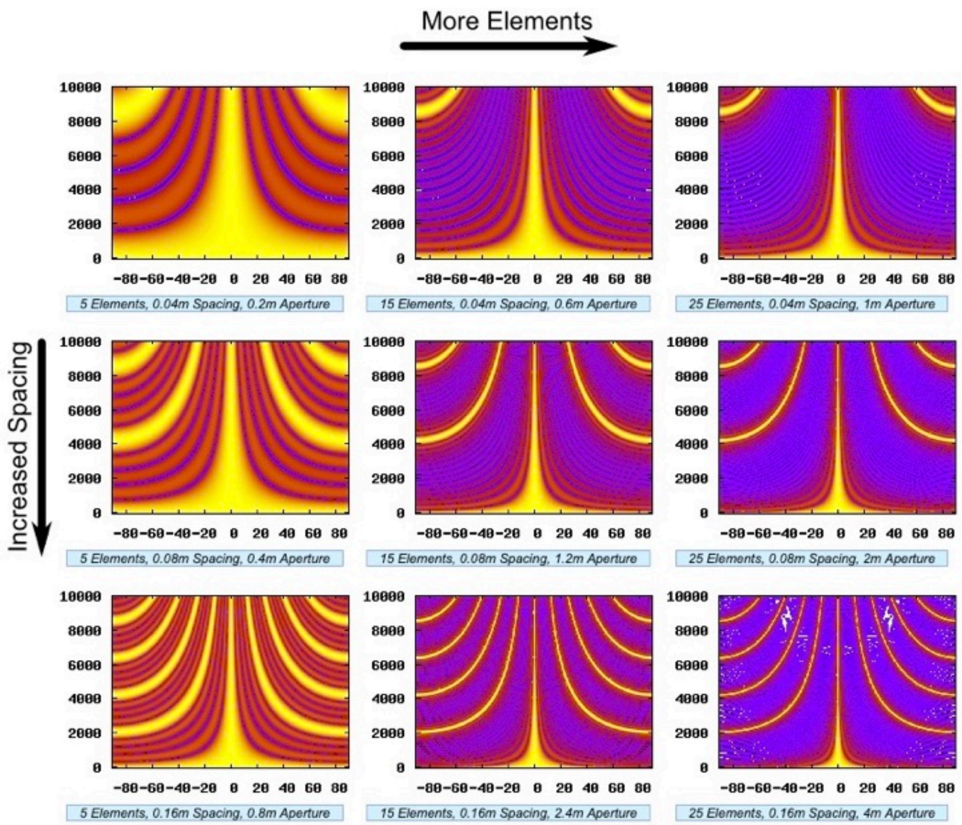
- largest factor influencing speed of sound is temperature
- speed of sound is ~343 m/s at 68° F,
- if the temperature deviates, the speed changes, which can alter perceived sound direction based on original delay values
- systems outdoors needs something to calibrate the delay values based on the temperature



Beamforming: Number of Mics

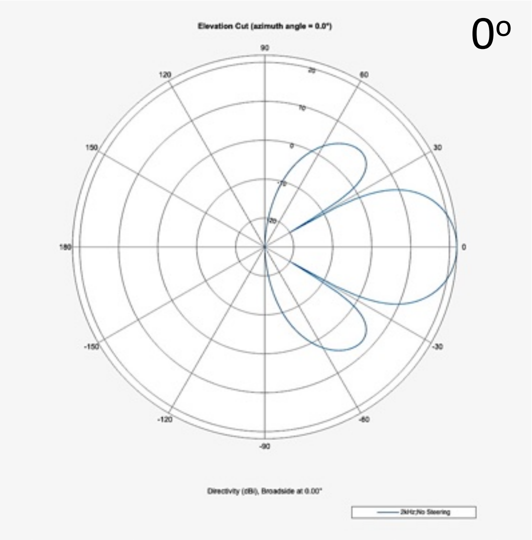
- more microphones allows for the formation of narrower beams
- narrower beams target sound more precisely, minimizing the interference from ambient noise and reverberations
- spatial aliasing at twice target frequency

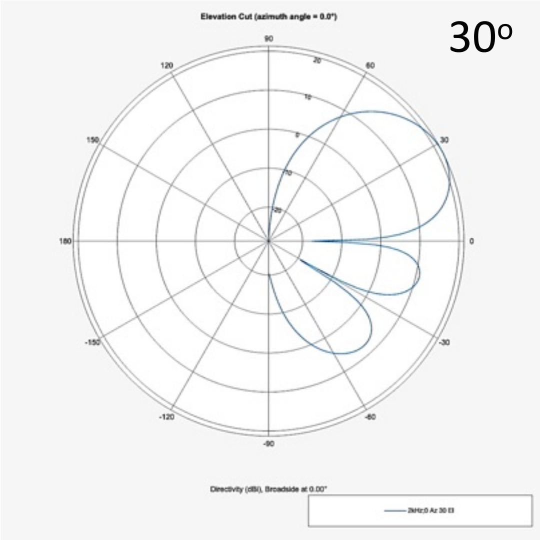
- will be using a 4x12 Uniform Rectangular Array (URA) centered around 2000Hz

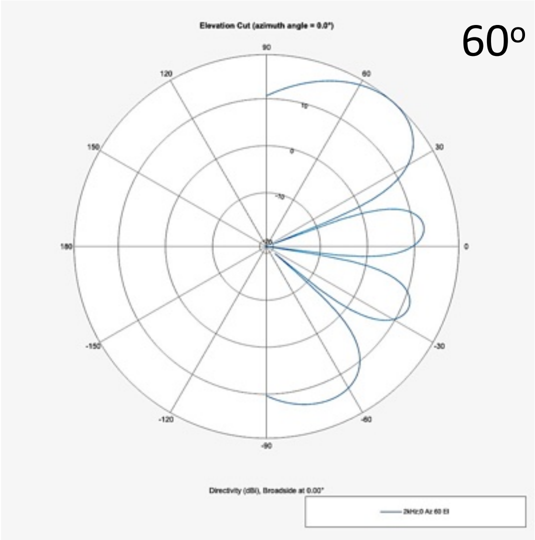


Beamforming: Simulations - 2D Azimuth

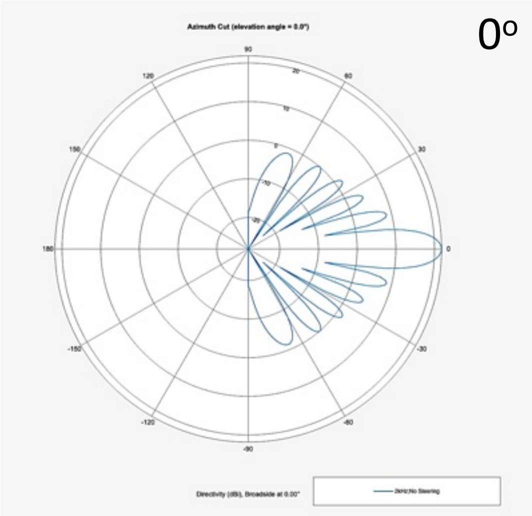
4 mics

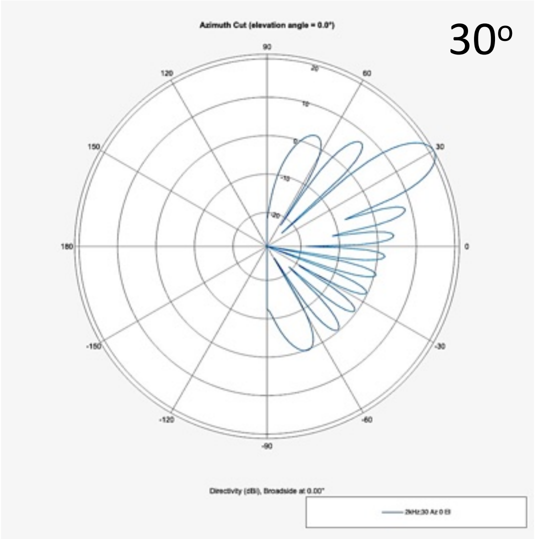


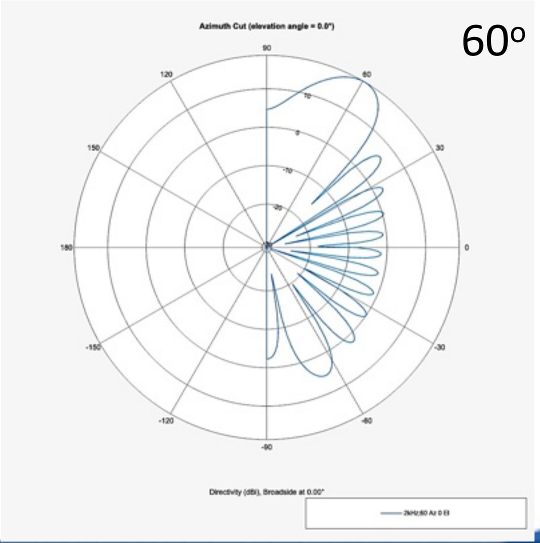




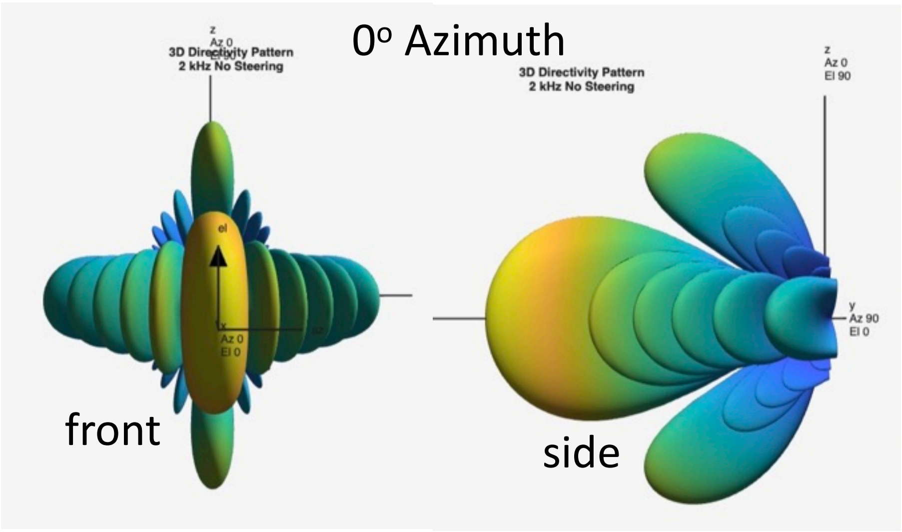
12 mics

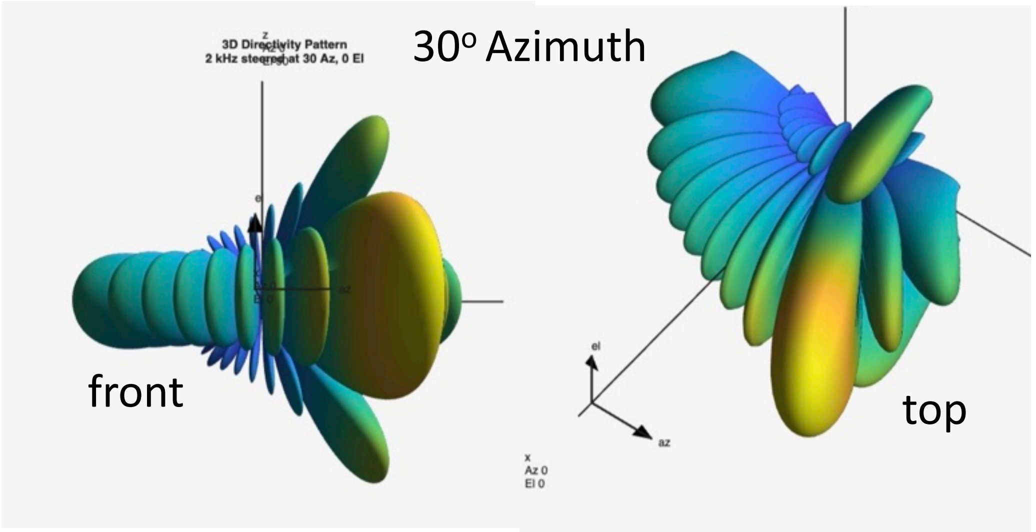


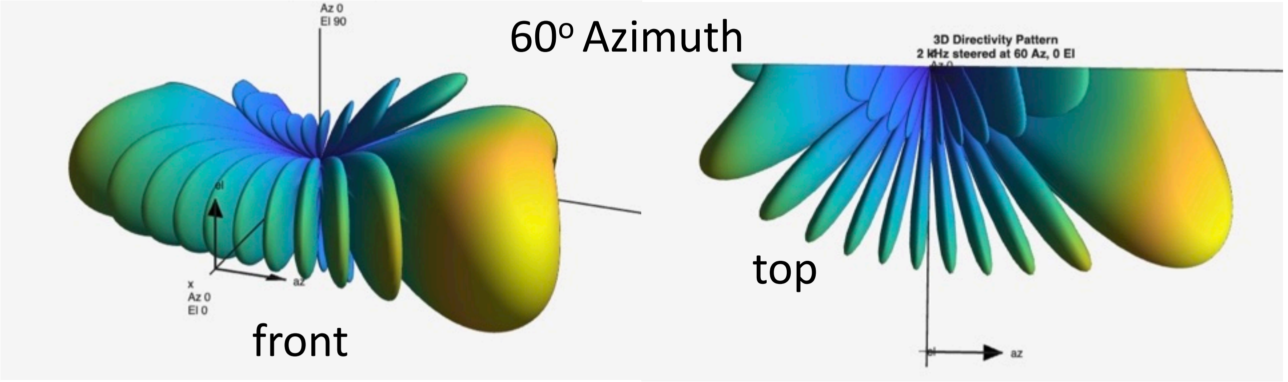


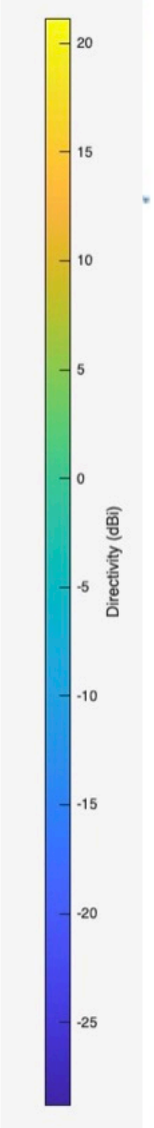


Beamforming: Simulations - 3D 4x12 Array

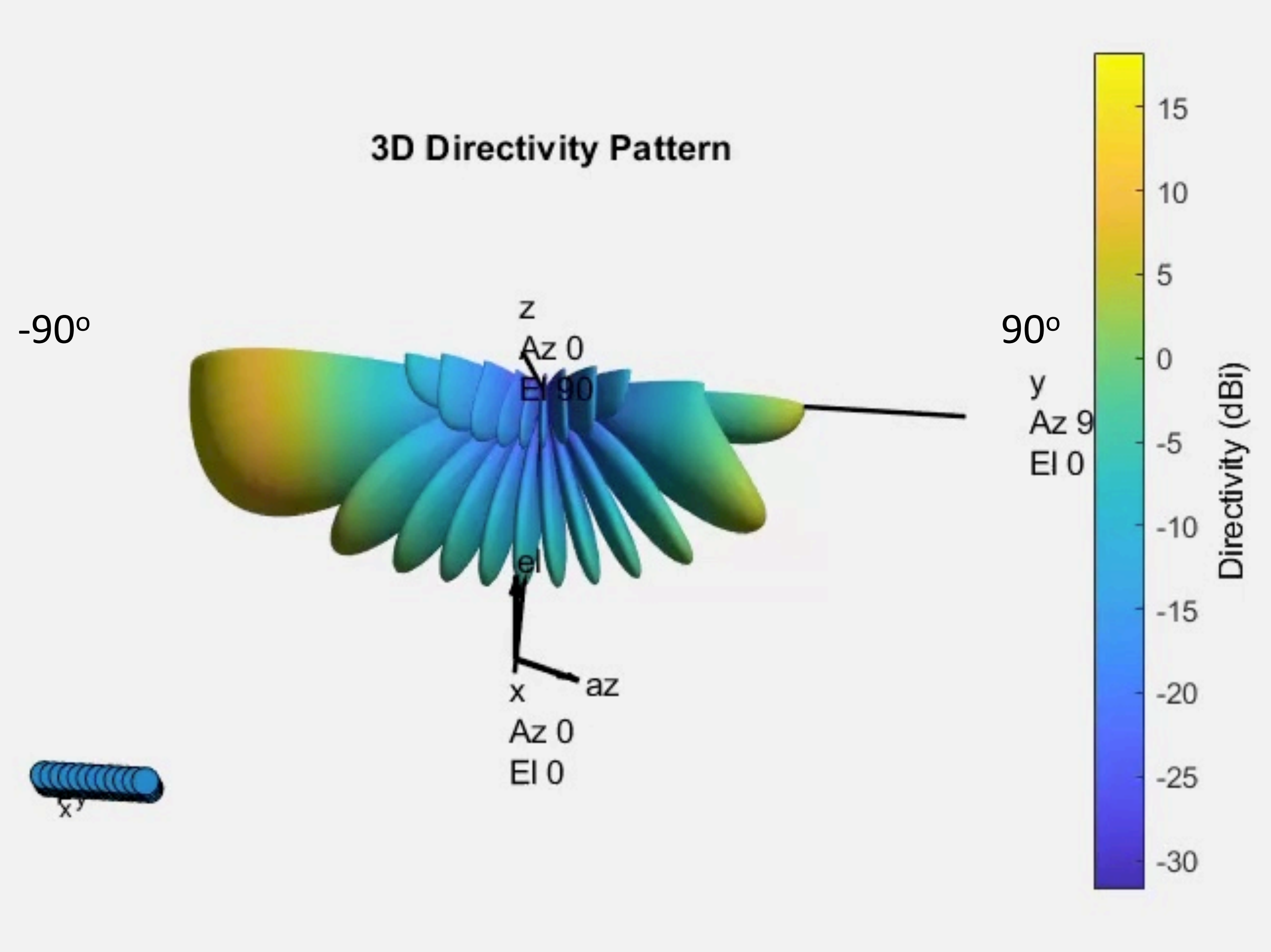








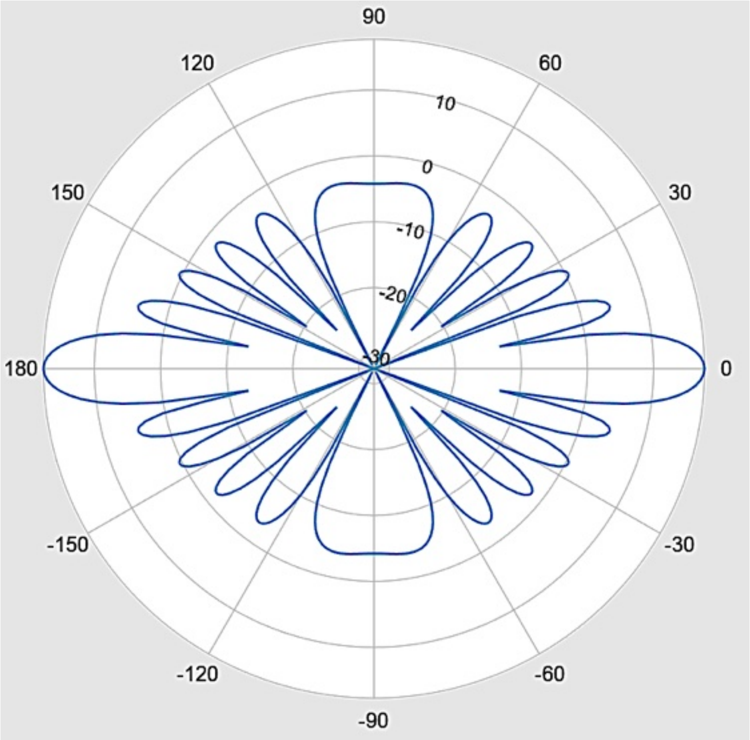
Beamforming: Simulations - 3D 4x12 Array



Sweep from -90 to 90 at 0° azimuth

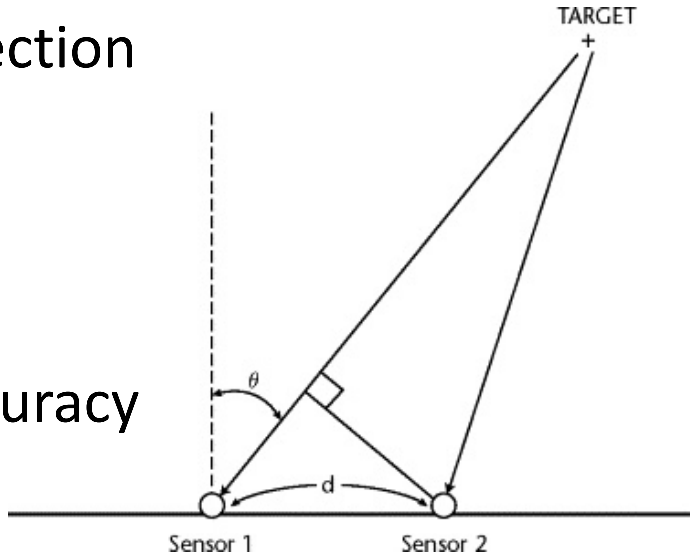
Beamforming: Weaknesses

- mic spacing is different when forming beams at diagonal angles: frequency response will be different in channels on diagonals than on axis
  - this is important to note for using these channels in deep learning applications
  - with a wide range of variation, it might cause issues with model accuracy
- Beam patterns are mirrored
  - Ideas for rear rejection would be foamed sound barrier wall or panel behind array
  - Add auxiliary mics for purposes of signal subtraction in mirrored lobes and rear sources



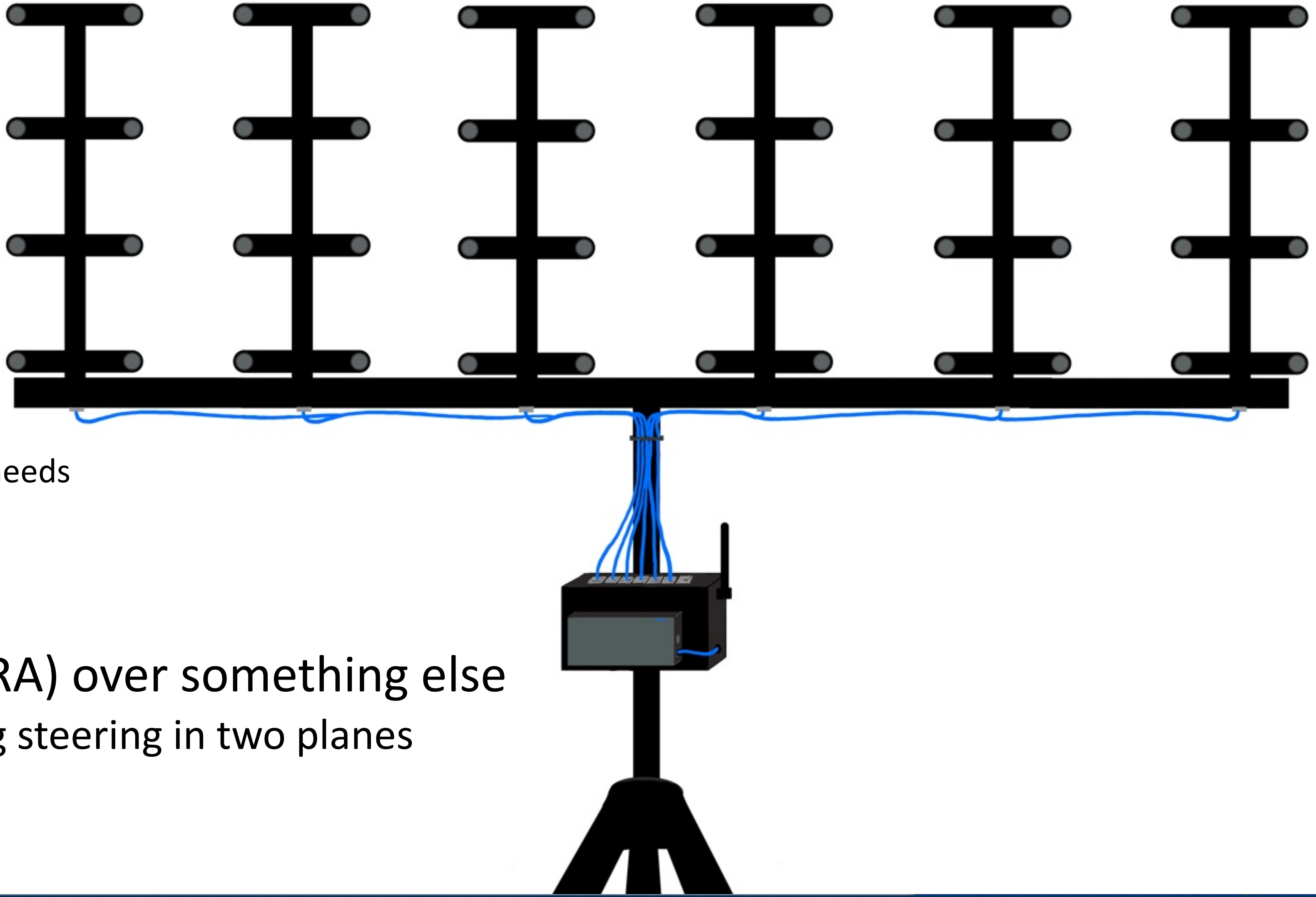
Time Direction-of-Arrival Estimation (TDAE)

- How does it work?
  - Similar concept for beamforming, but backwards
  - Find the delay of the transient event to determine its direction
- Why use it?
  - Finer direction resolution specially for transient events
  - Only gives direction, not audio channel
  - Used in combination with beamforming could bolster accuracy



Array Design

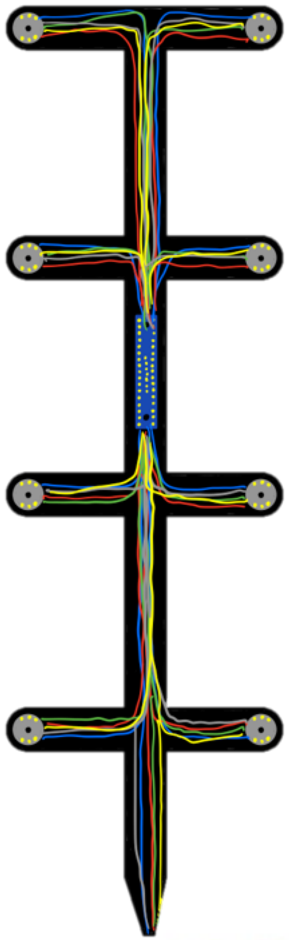
- Design considerations
  - Portability
  - Mounting Stability
  - Rear Sound Rejection
  - Ease of Creation:
    - duplicate parts for minimal design needs
    - interchangeable for flexibility
    - minimal materials needed



- Uniform Rectangular Array (URA) over something else
  - More control over beamforming steering in two planes
  - Computational efficiency

Array Design

- Pros
  - Wind resistant for improved sound quality and physical stabilization
  - Less material needed to demo and protype
  - Ability to breakdown parts makes transporting and deployment easier
  - Gives flexibility for different array configurations which suit different environments and situations
- Cons
  - Rejection from rear sources is not being directly addressed
  - ability to test with foam backing during characterization experiment
- Lab 3D printer constraints: 12x12x11.8in
  - Each antenna panel is less than 12in

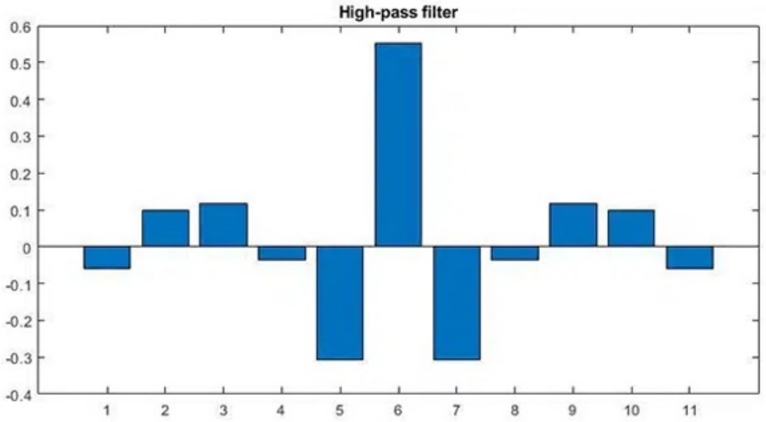


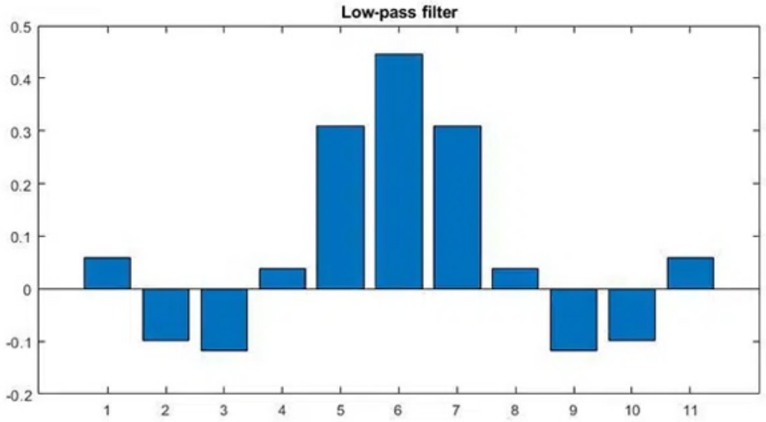
Finite Impulse Response (FIR) Filter

- Used to implement beamforming concept
- Digital filter with limited number of impulses
- Time Delays
- High, Low, & Band Pass Filters

$$y(n) = \sum_{k=0}^{M-1} b_k x(n-k)$$

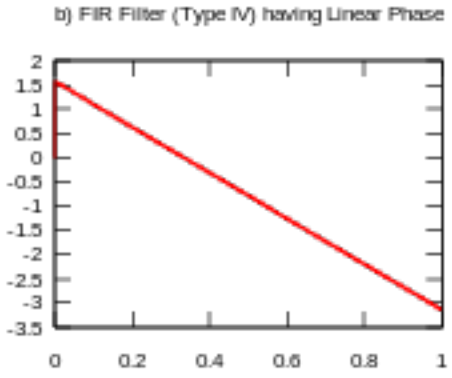
FIR Basic Equation

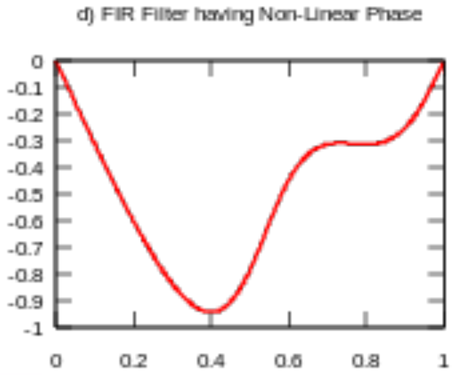


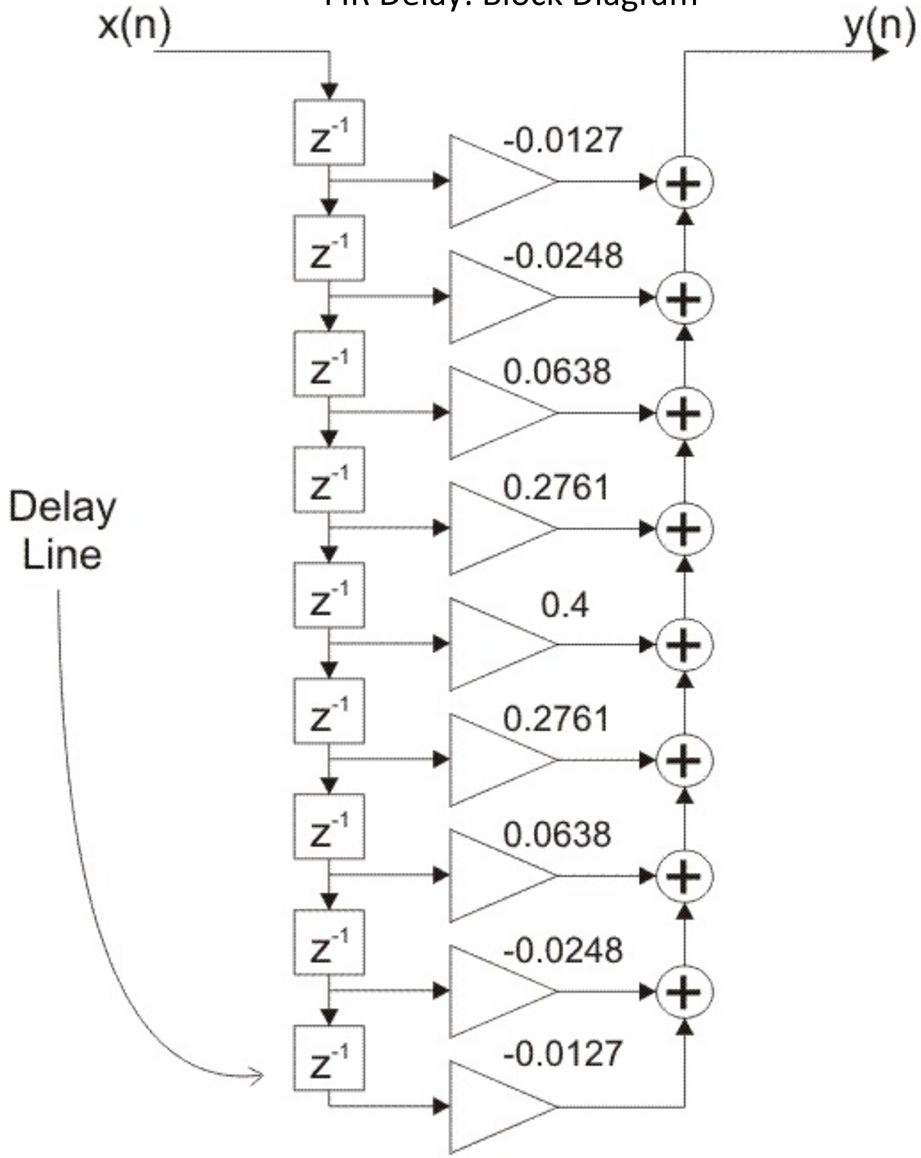


FIR Filter: Delays

- output = finite sequence of numbers, derived from the convolution of the input signal with a finite sequence of filter coefficients
- stable filter: even at resonant frequency
- linear phase response







FIR Filter: Design

- Group Delays: the derivative of the phase response, which represents the average delay of the filter across frequencies
  - Constant for linear phase response
- ideal impulse response of a simple delay filter is a Kronecker delta function shifted to the right by the desired number of samples
  - filter's output is a copy of its input delayed by a specific time period
  - impulse response of a delay filter is mostly zeros except for a one at the delay point
- dual purpose filter for frequency response correction from beamforming

FIR Filter: Design

- Windowing
  - used to control characteristics of filter by shaping impulse response
  - take ideal filter's impulse response and truncate it to a finite length for practical implementation
  - the truncation is achieved by multiplying the ideal impulse response with a window function which has non-zero values only within a certain interval and tapers to zero at the edges
  - windowing functions smooth out the abrupt ends of the truncated impulse response
  - for filters where the phase response and the exact timing of the signal are critical, windowing can manage and control the phase characteristics