Approximate Maximum-Likelihood (AML) Algorithm for Acoustical Beamforming and Localization

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Outline

1. Introd. to beamforming & acoustical array
2. Narrowband vs wideband beamforming
3. App. Max. Likelihood (AML) concept
4. AML implemented on Parc array
5. Early AML implemented on iPAQs
6. Various efforts in using AML
7. Recent work on using RST for SN
8. Conclusions

Beamforming

- **Beamforming** based on array processing can achieve:

1.Detect - declare whether one (or more) acoustic/seismic source(s) is (are) present

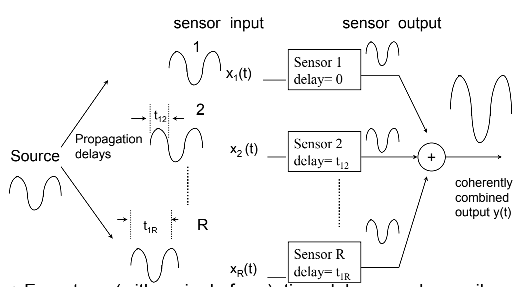
2.Enhance desired signal for obtain his SINR and reject/reduce unwanted signals/ noises

3. **Localize** one (or more) source(s) (by finding the direction-of-arrivals (DOAs) and their cross-bearings in the far-field) and range(s) and DOA(s) in the near-field
4. **Localize** the arrays in some local coordinate
5. **Classify** the source(s) based on spectral, spectrogram, HMM, etc. methods
6. **Tracking** of one (or more) sources by Kalman or particle filtering

Applications using Beamforming

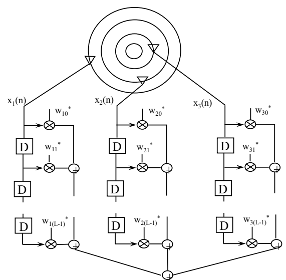
- Smart hearing-aid (relative to 1 microphone)
- Steer camera toward a speaker in teleconference application
- Detect/locate/track human speaker(s) in home security and military surveillance applications
- Detect/locate/track moving vehicle(s) in civilian/ military applications
- Detect/locate/track/classify animal(s) in biological studies

Narrowband Beamformer to Achieve Coherent Combining



- For a tone (with a single freq.), time delays can be easily achieved by phase control using a complex multipling weight

Wideband (WB) Beamforming



- Wideband beamformer needs multiple weights per channel
- Various methods can be used for the array weights

Approximate Maximum Likelihood (AML) Estimation Method

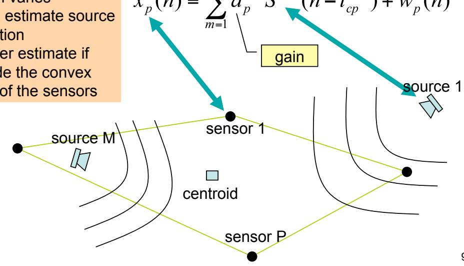
- ML method is a well-known statistical estimation tool (optimum for large SNR)
- We have formulated an approx. ML method for wideband signal for DOA, source localization, and optimal sensor placement in the freq. domain (Chen-Hudson-Yao, IEEE Trans. SP, Aug. 2002)
- AML method generally outperforms many suboptimal techniques such as closed-form least squares and wideband MUSIC solutions
- Has relative high complexity

Near-Field Data Model

Near-Field Case
- Wavefront is curved
- Gain varies
- Can estimate source location
- Better estimate if inside the convex hull of the sensors

time delay, noise, gain

$$x_p(n) = \sum_{m=1}^{M} a_p^{(m)} S^{(m)}(n - t_{cp}^{(m)}) + w_p(n)$$

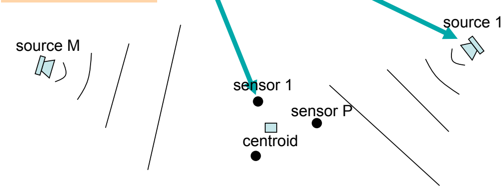


Far-Field Data Model

Far-Field Case
- Wavefront is planar
- Gain is unity
- can only estimate bearing

time delay, noise

$$x_p(n) = \sum_{m=1}^{M} S^{(m)}(n - t_{cp}^{(m)}) + w_p(n)$$



Wideband AML Algorithm (1)

Data Model

$$x_p(n) = \sum_{m=1}^{M} S^{(m)}(n - t_{cp}^{(m)}) + w_p(n)$$

FFT

Freq Domain Model (WGN)

$$\mathbf{X}(k) = \mathbf{D}(k)\mathbf{S}(k) + \eta(k), k = 1, \ldots, N/2$$

$$= \begin{bmatrix} e^{j2\pi k t_{c1}^{(1)}/N} & \cdots & e^{j2\pi k t_{c1}^{(M)}/N} \\ \vdots & \ddots & \vdots \\ e^{j2\pi k t_{cp}^{(1)}/N} & \cdots & e^{j2\pi k t_{cp}^{(M)}/N} \end{bmatrix} \begin{bmatrix} S_1(k) \\ \vdots \\ S_M(k) \end{bmatrix} + \eta(k)$$

Each column is a steering vector for each source

Likelihood function

$$\max_{\Theta,\mathbf{S}} L(\Theta, \mathbf{S}) = \min_{\Theta,\mathbf{S}} \sum_{k=1}^{N/2} \| \mathbf{X}(k) - \mathbf{D}(k)\mathbf{S}(k) \|^2$$

Wideband ML Algorithm (2)

Likelihood function

$$\max_{\Theta,\mathbf{S}} L(\Theta, \mathbf{S}) = \min_{\Theta,\mathbf{S}} \sum_{k=1}^{N/2} \| \mathbf{X}(k) - \mathbf{D}(k)\mathbf{S}(k) \|^2$$

$$\hat{\mathbf{S}}(k) = \mathbf{D}^{+}(k)\mathbf{X}(k)$$

Summation in Frequency

Simpler Likelihood function

$$\max_{\Theta} J(\Theta) = \max_{\Theta} \sum_{k=1}^{N/2} \| \mathbf{P}(k,\Theta)\mathbf{X}(k) \|^2$$

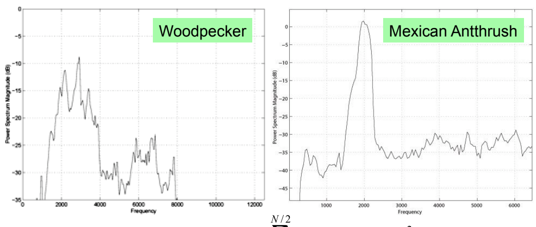
$$\mathbf{P}(k,\Theta) = \mathbf{D}(k,\Theta)\mathbf{D}^{+}(k,\Theta)$$

Estimated DOA

Source Estimate

$$\hat{\mathbf{S}}_{ML}(k) = \mathbf{D}^{+}(k, \Theta_{ML})\mathbf{X}(k), k = 1, \ldots, N/2$$

Source Spectrum



$$\max_{\Theta} J(\Theta) = \max_{\Theta} \sum_{k=1}^{N/2} \| \mathbf{P}(k,\Theta)\mathbf{X}(k) \|^2$$

Frequency bins with higher PSD will contribute more to the likelihood

Single source: $\| \mathbf{PX} \|^2 = \| \mathbf{DD}^{+}\mathbf{D}S \|^2 = \| \mathbf{DD}^{+}\mathbf{D} \|^2 |S|^2$

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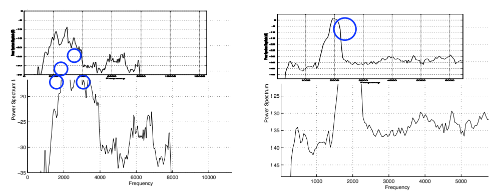

Vocalization of Acorn Woodpecker

Vocalization of Mexican Antthrush

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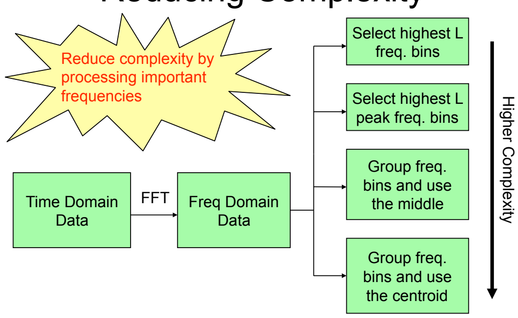
Reducing Complexity



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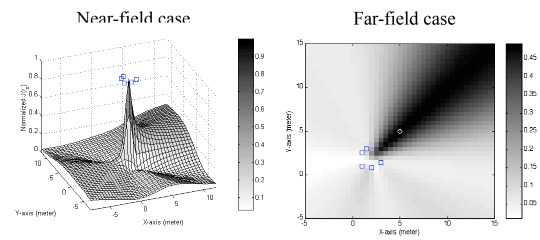
AML Metric Plot

- Peak at source location in near-field case
- Broad "lobe" along source direction in far-field case
- Sampling frequency f_s = 1KHz, SNR = 20dB



□ - sensor locations

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Semi-Anechoic Room at Xerox-Parc

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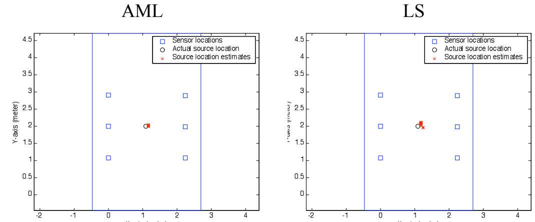
Indoor Convex Hull Exp. Results

- Semi-anechoic room, SNR = 12dB
- Direct localization of an omni-directional speaker playing the LAV (light wheeled vehicle) sound
- AML RMS error of 73 cm, LS RMS error of 127cm



Outdoor Testing at Xerox-Parc

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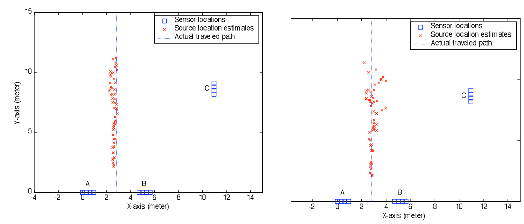
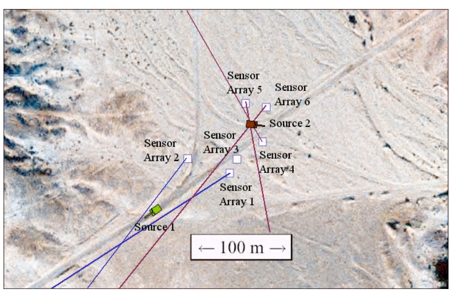
Outdoor Moving Source Exp. Results

- Omni-directional speaker playing the LAV sound while moving from north to south
- Far-field: cross-bearing of DOAs from 3 subarrays

AML LS



AML Sensor Network at 29 Palms



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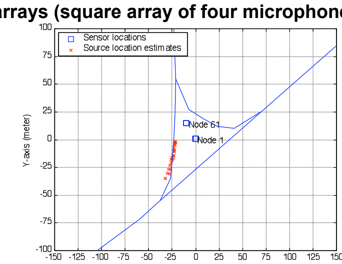
29 Palms Field Measured Localization

- Single AAV traveling at 15mph
- Far-field situation: cross-bearing of DOAs from two subarrays (square array of four microphones, 1ft spacing)



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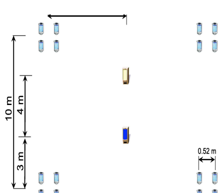
Free Space Experiment using iPAQS



Square subarray configuration

Each subarray consists of four iPAQs with its microphone, cps, and 802.11b wireless card

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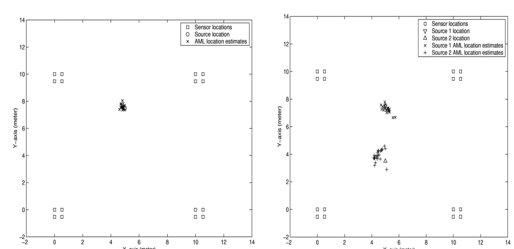
Free Space Experimental Results



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Review of narrowband beamforming of a uniform linear array (ULA)

- **Consider a narrowband source with wavelength λ**
  - **If the inter-element spacing d >λ/2, grating lobes (lobe of the same height of the mainlobe) will appear in the beampattern and results in ambiguities in the DOA estimation. (spatial aliasing effect)**
  - **The width of the lobes become narrower as d increases. (resolution improves)**
- **For wideband signals, the beam-pattern is an average of the beam-pattern of all frequency components.**
  (grating lobes become side-lobes)
- **Uniform circular array is considered in our design, since we have no preference in any azimuth angle.**

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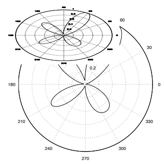
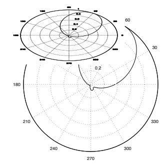
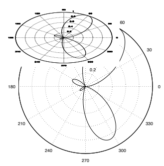
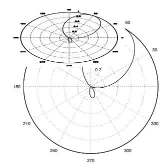

Woodpecker, r=7.07 cm


Woodpecker, r=2.83 cm


Antthrush, r=6.10 cm


Antthrush, r=4.24 cm

Beampattern of a 4-element UCA. True DOA=60 degree

Some facts:
Aperture ↗
1)Width of mainlobe ↘ (better resolution)
2)Number of sidelobes ↗ (less robust)

Optimal array size is highly dependent on the source spectrum

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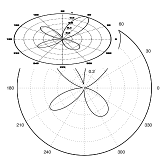
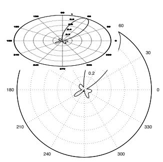

Woodpecker, r=7.07 cm, 4 elements


Woodpecker, r=7.07 cm, 8 elements

For fixed aperture size, sidelobes ↘ as number of elements ↗

In our applications of interest, there will always be reverberation and ambient noise, which can increase the magnitude of sidelobes and result in false estimate.

Therefore parameters of a robust Array should be chosen s.t.

$$\frac{\text{Magnitude of main lobe}}{\text{Magnitude of largest sidelobe}} > \text{Threshold}$$

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AML Beamforming to Separate Two Sources

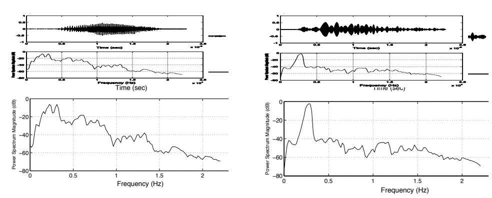

Fig. 1 (Left top) Woodpecker waveform; (Right top) Dusky AntBird waveform; (Left bottom) Woodpecker spectrum; (Right bottom) Dusky AntBird spectrum.

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DOA Estimation of Combined Source

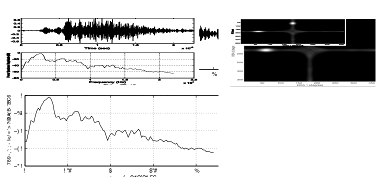

Fig. 2 (Left top) Combined Woodpecker and Dusky AntBird waveform ; (Left bottom) Combined Woodpecker and Dusky AntBird spectrum;
(Right) Estimated DOAs of two sources at 60 deg. and 180 deg.

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Separated Waveforms/Spectra by AML Beamforming

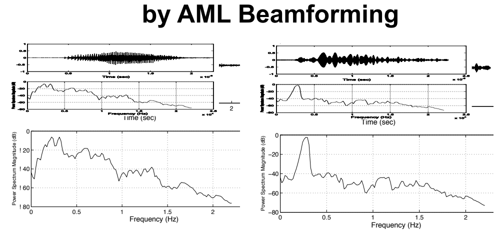

Fig. 3. (Left) Separated Woodpecker waveform and spectrum;
(Right) Separated Dusky AntBird waveform and spectrum.

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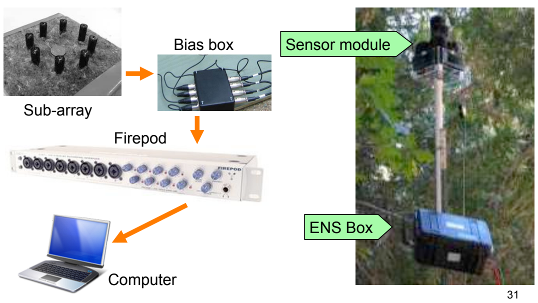
Data Collection Platforms

Firepod Based Acoustic Sensor Platform

Acoustic ENS Platform



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Acoustic ENS Box Platform

Acoustic ENSBox V1
(2004-2005)

- Wireless distributed system
- Self-contained
- Self-managing
- Self-localization
- Processors
- Microphone array
- Omni directional speaker

V2 (2007)

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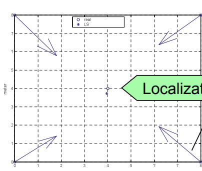
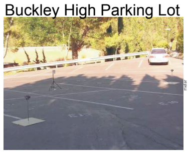
Localization Experiment (1)

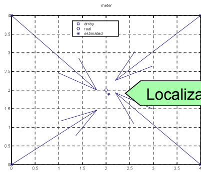
UCLA Science Courtyard



Buckley High Parking Lot



- Array size is 8 m
- Source is Woodpecker



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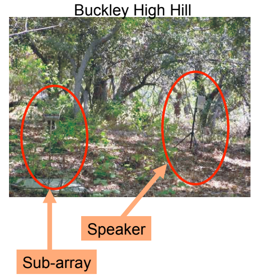
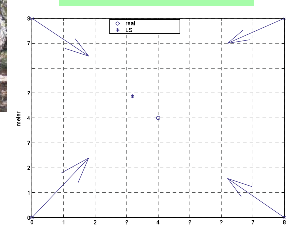
Localization Experiment (2)

Buckley High Hill



Localization Error ~1.19 m



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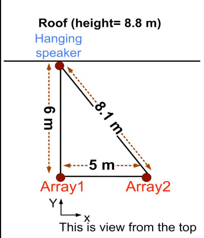
3D Array-Experiment Setup (A)



Array1 and Array2 are 5 m apart.

A Speaker is hanging from the roof with different heights and plays a woodpecker call audio file.

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Experimental 3D Results

- speaker on the roof (h=8.8 m)

	AZ	EL
Girod_1	93 (90)	51 (54)
Iso_1	89 (90)	53 (55)
Girod_2	132 (130)	50 (46)

The accuracy of estimated DOAs for all the three subarrays is acceptable. (error<4 degrees).

Performance of iso_1 is a little bit better than Girod_1.

- Red numbers are true angles in degree
- Black numbers are estimated angles in degree.

- speaker with height of 7.8 meter

	AZ	EL
Girod_1	91 (90)	53 (50)
Iso_1	90 (90)	50 (52)
Girod_2	127 (130)	46 (42)

The accuracy of estimated DOAs for all the three subarrays is acceptable. (error<4 degrees).

Performance of iso_1 is a little bit better than Girod_1.

- Red numbers are true angles in degree
- Black numbers are estimated angles in degree.

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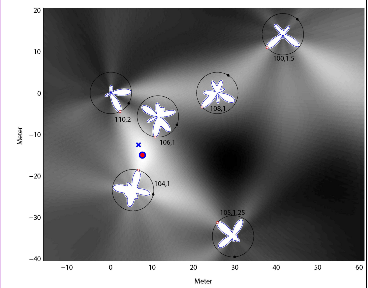
Satellite Picture of Deployment

- Rocky Mountain Biological Laboratory (RMBL), Colorado
- 6 Sub-arrays
- Burrow near Spruce
- Wide deployment
  - Max range ~ 140 m
- Compaq deployment
  - Max range ~ 50 m

Pseudo Log-Likelihood Map

- Compaq deployment
- × location estimate
- ● spruce location
- Normalized beam pattern
- Collective result mitigate individual sub-array ambiguities
- Marmot observed near Spruce



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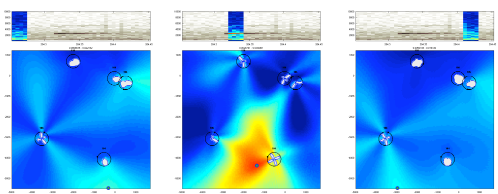
Field Measurements at RMBL



Plots of the spectrogram as a function of time (top figures) and plots of the AML array gain patterns of five wireless subarray nodes (bottom figures).
When the marmot call is present in the middle figure, all DOAs point toward the marmot, yielding its localization. The redness of an area indicates a greater likelihood of the sound. (IPSN07)

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Introduction to RST

- Traditional randomness in continuous channel noise is well understood
- In sensor networks, discrete randomness in the form of number of targets (birds) and number of active sensors have not been jointly optimized with channel randomness
- Random set theory (RST) allows the use of set theory to model real life situations with full mathematical/logical consistency

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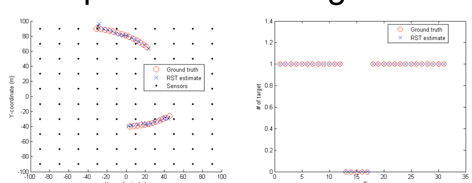
Simple RST Tracking Results



- The two separate tracks may come from two distinct targets at different times
- The tracker jointly detects the number of target and its position simultaneously

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Conclusions

- Use of beamforming for localization and enhancement of desired signal and reduction of unwanted signals
- Introduced the AML beamforming concept
- Discussed tradeoffs in array design (e.g., configuration, size, no. of microphones, etc.)
- Various examples of AML results
- Brief introduction to possible RST method to possible sensor network problems

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