Sensor Networks, Aeroacoustics, and Signal Processing

Part II: Aeroacoustic Sensor Networks

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Heterogeneous Network of Acoustic Sensors

**Issues:**
- Centralized versus distributed processing
- Minimize comms., energy
- Triangulation, TDOA?
- Effects of acoustic prop.
- (Node localization, sensor layout & density, Classification, tracking)
Acoustic Source & Propagation

Source:
- Loud
- Spectral lines

Turbulence scatters wavefronts

One sensor:
- Detection
- Doppler estimation
- Harmonic signature

Signal at sensor (mic.)

DSP

SPECTROGRAM OF SENSOR 1 (dB)
More Sophisticated Node: Sensor Array

Issues:
- Array size/baseline
  - Coherence decreases with larger spacing
- AOA estimation accuracy with turbulent scattering
- What can we do with a hockey-puck sensor?
  - Small, covert, easily deployable
  - Performance?
Why Acoustics?

- Advantages:
  - Mature sensor technology (microphones)
  - Low data bandwidth: \(\sim[30, 250]\) Hz
    \(\Rightarrow\) Sophisticated, real-time signal proc.
  - Loud sources, difficult to hide: vehicles, aircraft, ballistics

- Challenges:
  - Ultra-wideband regime: 157% fractional BW
  - \(\lambda\) in \([1.3, 11]\) m \(\Rightarrow\) Small array baselines
  - Propagation: turbulence, weather, (multipath)
  - Minimize network communications

- We bound the space of useful system design and performance [Kozick2004a]
  - with respect to SNR, range, frequency, bandwidth, observation time, propagation conditions (weather), sensor layout, source motion/track
  - evaluate performance of algorithms (simulated & measured data)
Brief History of Acoustics in Military [Namorato2000]

- Trumpeting down walls of Jericho
  - Chinese, Roman (B.C.)
  - Civil War: Generals used guns to signal attacks
  - World War 1: Science of acoustics developed
    - Air & underwater acoustic systems
  - World War 2: Mine actuating, submarine detection
  - Many developments …
  - Army Research Laboratory, 1991-present [Srour1995]
    - Hardware and software for detection, localization, tracking, and classification
    - Extensive field testing in various environments with many vehicle types
Remainder of Tutorial

• A little more background:
  – Source characteristics
  – Sound propagation through turbulent atmosphere

• Detection of sources (Saturation, $\Omega$)

• Array processing
  – Coherence loss from turbulence (Coherence, $\gamma$)
  – Array size: 2 sensors $\Rightarrow$ source AOA
  – Array of arrays $\Rightarrow$ source localization
    Distributed processing? Data to transmit?
    Triangulation/TDOA Minimize comms.

Experimentally validated models
Source Characteristics

- Ground vehicles (tanks, trucks), aircraft (rotary, jet), commercial vehicles, elephant herds ➔ LOUD

- Main contributors to source sound:
  - Rotating machinery: Engines, aircraft blades
  - Tires and “tread slap” (spectral lines)
  - Vibrating surfaces

- Internal combustion engines: Sum-of-harmonics due to cylinder firing

- Turbine engines: Broadband “whine”

- Key features: Spectral lines and high SNR

Distinct from underwater
+/- 350 m from Closest Point of Approach (CPA)
Harmonic lines

Doppler shift:
0.5 Hz @ 14.5 Hz
⇒ 3 Hz @ 87 Hz

+/− 85 m from CPA

CPA = 5 m
15 km/hr

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Overview of Propagation Issues

• “Long” propagation time: 1 s per 330 m
• Additive noise: Thermal, Gaussian (also wind and directional interference)
• Scattering from random inhomogeneities (turbulence) $\Rightarrow$ temporal & spatial correl.
  – Random fluctuations in amplitude: $\Omega$
  – Spatial coherence loss (>1 sensor): $\gamma$
• Transmission loss: Attenuation by spherical spreading and other factors
Transmission Loss

- Energy is diminished from $S_{\text{ref}}$ (at 1 m from source) to $S$ at sensor:
  - Spherical spreading
  - Refraction (wind, temp. gradients)
  - Ground interactions
  - Molecular absorption

We model $S$ as a deterministic parameter:

$\Rightarrow$ **Average** signal energy

Numerical Solution [Wilson2002]

[Embleton1996]
Measured Aeroacoustic Data
Measured SNR vs. Range & Frequency

Fluctuations due to turbulence

SNR ~ 50 dB at CPA

Aspect dependence

Array 1: Mean SNR in 5 Hz bands for moving source

Array 2: Mean SNR in 5 Hz bands for moving source

Array 3: Mean SNR in 5 Hz bands for moving source

Array 4: Mean SNR in 5 Hz bands for moving source

Array 5: Mean SNR in 5 Hz bands for moving source

Array 6: Mean SNR in 5 Hz bands for moving source
Outline

- Detection of sources
  - Saturation, $\Omega$
  - Detection performance

- Array processing
  - Coherence loss from turbulence, $\gamma$
  - Array size: 2 sensors
    $\Rightarrow$ Source AOA
  - Array of arrays:
    $\Rightarrow$ Source localization

Triangulation/TDOA, minimize comms.

Sinusoidal signal emitted by moving source:

$$s_{ref}(t) = \sqrt{S_{ref}} \cos(2\pi f_o t + \chi)$$

1. Propagation delay, $\tau$
2. Additive noise
3. Transmission loss
4. Turbulent scattering

Signal at the sensor:

$$z(t) = s(t - \tau) + w(t)$$
Sensor Signal: No Scattering

- Sensor signal with transmission loss, propagation delay, and AWG noise:
  \[ z(t) = s(t - \tau) + w(t), \quad t_o \leq t \leq t_o + T \]
  \[ s(t) = \sqrt{S} \cos(2\pi f_o t + \chi), \quad \tau = \text{propagation time} \]

- Complex envelope at frequency \( f_o \)
  - Spectrum at \( f_o \) shifted to 0 Hz
  - FFT amplitude at \( f_o \)
    \[ \tilde{z}(t) = \sqrt{S} \exp[j(\chi - \omega_o \tau)] + \tilde{w}(t) \]
    \[ = \sqrt{S} \exp[j\theta] + \tilde{w}(t) \]
Sensor Signal: With Scattering

• A fraction, $\Omega$, of the signal energy is scattered from a pure sinusoid into a zero-mean, narrowband, Gaussian random process, $\tilde{v}(t)$:

$$\tilde{z}(t) = \sqrt{(1-\Omega)S} \exp[j\theta] + \sqrt{\Omega S} \tilde{v}(t) \exp[j\theta] + \tilde{w}(t)$$

• **Saturation parameter**, $\Omega$ in $[0, 1]$  
  – Varies w/ source range, frequency, and meteorological conditions (sunny, windy)
  – Based on physical modeling of sound propagation through random, inhomogeneous medium

• Easier to see scattering effect with a picture:
• Study detection of source, w/ respect to
  – Saturation, $\Omega$ (analogous to Rayleigh/Rician fading in comms.)
  – Processing bandwidth, $B$, and observation time, $T$
  – $\text{SNR} = S / (2N_0B)$
  – Scattering bandwidth, $B_v < 1 \text{ Hz}$ (correlation time $\sim 1/B_v > 1 \text{ sec}$)
  – Number of independent samples $\sim (T B_v)$ often small

• Scattering ($\Omega > 0$) causes signal energy fluctuations
Probability Distributions

- Complex amplitude has complex Gaussian PDF with non-zero mean:
\[ \tilde{z} \sim \text{CN}(e^{j\theta} \sqrt{(1-\Omega)S}, \Omega S + \sigma^2) \]

- Energy \( P = |\tilde{z}|^2 \) has non-central \( \chi \)-squared PDF with 2 d.o.f.

- \( \sqrt{P} \) has Rice PDF

(Experimental validation in [Daigle1983, Bass1991, Norris2001])
Saturation vs. Frequency & Range

• Saturation depends on [Ostashev2000]:
  – Weather conditions (sunny/cloudy), but varies little with wind speed
  – Source frequency $\omega$ and range $d_o$

\[ d_o = \text{range of source (m)}, \quad \omega = \text{frequency (rad/sec)} \]

\[ \Omega = 1 - \exp(-2\mu d_o) \]

\[ \mu(\omega) \approx \begin{cases} 4.03 \times 10^{-7} \left( \frac{\omega}{2\pi} \right)^2, & \text{mostly sunny} \\ 1.42 \times 10^{-7} \left( \frac{\omega}{2\pi} \right)^2, & \text{mostly cloudy} \end{cases} \]

\[ = \kappa_1(\text{weather}) \cdot \omega^2 \]

Theoretical forms

Constants from numerical evaluation of particular conditions
Turbulence effects are small only for very short range and low frequency.

Saturation varies over entire range [0, 1] for typical range & freq. values.
Detection Performance

\( P_D = \text{probability of detection} \)
\( P_{FA} = \text{probability of false alarm} \)

No scattering

Full scattering

Scattering begins to limit performance
Detection Performance with Range

SNR = 50 dB at 10 m range
SNR \sim 1/(\text{range})^2

Lower frequencies detected at larger ranges

Saturation increases with
- Range
- Frequency
- Temperature (sunny)
Detection Extensions

- Sensor networks: Detection ➔ queuing (wake-up) of more sophisticated sensors
- Multiple snapshots & frequencies
  - Source motion & nonstationarities
  - Coherence time of scattering
- Multiple sensors with different SNR and $\Omega$
  - Distributed detection, what to communicate?
  - Required sensor density for reliable detection
  - Source localization based on energy level at the sensors [Pham2003]

Physical models for cross-freq coherence and coherence time are in preliminary stage [Norris2001, Havelock1998]
Outline

- **Detection of sources**
  - Saturation, $\Omega$
  - Detection performance

- **Array processing**
  - Coherence loss from turbulence, $\gamma$
  - Array size: 2 sensors
    - Source AOA
  - Array of arrays:
    - Source localization
    - Triangulation/TDOA, minimize comms.

Coherence, $\gamma$, depends on

- Sensor separation, $\rho$
- Source frequency, $\omega$
- Source range, $d_o$
- Weather conditions: sunny/cloudy, wind speed
Signal Model for Two Sensors

\[ \tilde{z} = \begin{bmatrix} \tilde{z}_1 \\ \tilde{z}_2 \end{bmatrix} \sim \text{CN}(e^{j\chi} \sqrt{1-\Omega} S \mathbf{a}, (\Omega S) \Gamma \circ (\mathbf{a} a^H) + \sigma^2 \mathbf{I}) \]

\[ \mathbf{a} = \begin{bmatrix} 1 \\ \exp(j\phi) \end{bmatrix}, \quad \theta = \text{AOA} = \arcsin(\phi c_o / (\omega \rho)) \]

\[ \phi = \text{phase} = (\omega / c_o) \rho \sin \theta \]

\[ \Omega = \text{Saturation} \in [0,1] \]

\[ \Gamma = \begin{bmatrix} 1 & \gamma \\ \gamma & 1 \end{bmatrix}, \quad \gamma = \text{Coherence} \in [0,1] \]

Turbulence effects

Perfect plane wave:
\[ \Omega = 0 \text{ or } 1 \]
\[ \gamma = 1 \]
Model for Coherence, $\gamma$

- Assume AOA $\theta = 0$, freq. in [30, 500] Hz
- Recall saturation model:
  \[ \Omega = 1 - \exp\left[-2\kappa_1(\text{weather})\omega^2 d_o\right] \]
- Coherence model [Ostashev2000]:
  \[ \gamma = \frac{\exp\left[-\kappa_2(\text{weather})\omega^2 \rho^{5/3} d_o\right] - (1 - \Omega)}{\Omega} \], $\rho << L_{\text{eff}}$
  $0 \leq \gamma \leq 1$

$$\kappa_2(\text{weather}) = \frac{0.137}{c_o^2} \left(\frac{C_T^2}{T_o^2} + \frac{22}{3} \frac{C_v^2}{c_o^2}\right)$$

$\gamma \to 0$ with freq., sensor spacing, and range

Temperature fluctuations

Velocity fluctuations (wind)
$$\gamma = \frac{\exp[-\kappa_2(\text{weather})\omega^2 \rho^{5/3} d_o] - (1 - \Omega)}{\Omega}, \quad \rho \ll L_{\text{eff}}$$

$$0 \leq \gamma \leq 1$$

$$\kappa_2(\text{weather}) = \frac{0.137}{c_o^2} \left( \frac{C_T^2}{T_o^2} + \frac{22}{3} \frac{C_v^2}{c_o^2} \right)$$

<table>
<thead>
<tr>
<th>Atmospheric condition</th>
<th>$\mu^{-1}$ (m) at 50 Hz</th>
<th>$\mu^{-1}$ (m) at 200 Hz</th>
<th>$C_T^2/T_o^2$ (m$^{-2/3}$)</th>
<th>$(22/3)C_v^2/c_o^2$ (m$^{-2/3}$)</th>
<th>$L_{\text{eff}}$ (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mostly sunny, light wind</td>
<td>990</td>
<td>62</td>
<td>$2.0 \times 10^{-5}$</td>
<td>$8.0 \times 10^{-6}$</td>
<td>100</td>
</tr>
<tr>
<td>Mostly sunny, moderate wind</td>
<td>980</td>
<td>61</td>
<td>$7.6 \times 10^{-6}$</td>
<td>$2.8 \times 10^{-5}$</td>
<td>91</td>
</tr>
<tr>
<td>Mostly sunny, strong wind</td>
<td>950</td>
<td>59</td>
<td>$2.4 \times 10^{-6}$</td>
<td>$1.3 \times 10^{-4}$</td>
<td>55</td>
</tr>
<tr>
<td>Mostly cloudy, light wind</td>
<td>2900</td>
<td>180</td>
<td>$1.5 \times 10^{-6}$</td>
<td>$4.4 \times 10^{-6}$</td>
<td>110</td>
</tr>
<tr>
<td>Mostly cloudy, moderate wind</td>
<td>2800</td>
<td>180</td>
<td>$4.5 \times 10^{-7}$</td>
<td>$2.4 \times 10^{-5}$</td>
<td>75</td>
</tr>
<tr>
<td>Mostly cloudy, strong wind</td>
<td>2600</td>
<td>160</td>
<td>$1.1 \times 10^{-7}$</td>
<td>$1.2 \times 10^{-4}$</td>
<td>28</td>
</tr>
</tbody>
</table>

(From [Kozick2004a], based on [Ostashev2000, Wilson2000])

Depends on wind level and sunny/cloudy
Assumptions for Model Validity  [Kozick2004a]

- Line of sight propagation (no multipath) ➜ appropriate for flat, open terrain
- AWGN is independent from sensor to sensor ➜ ignores wind noise, directional interference
- Scattered process is complex, circular, Gaussian [Daigle1983, Bass1991, Norris2001]
- Wavefronts arrive at array aperture with near-normal incidence
- Sensor spacing, $\rho$, resides in the *inertial subrange* of the turbulence:

  
  \[
  \text{smallest turbulent eddies} \ll \rho \ll \text{largest turbulent eddies} = L_{\text{eff}}
  \]

\[
\gamma = \exp\left[-\kappa_2(\text{weather}) \quad \frac{\omega^2 \rho^{5/3} d_o}{\Omega} \left(1 - \Omega\right)\right] \rightarrow 0 \quad \text{for} \quad \rho \gg L_{\text{eff}}
\]
\[
\exp\left[-\kappa_2(\text{weather}) \quad \frac{\omega^2 \rho^{5/3} d_o}{\Omega} \right] \rightarrow (1 - \Omega) \quad \text{for} \quad \rho \gg L_{\text{eff}}
\]
Coherence, $\gamma$, versus frequency and range for sensor spacing $\rho = 12$ inches

Coherence, $\gamma$, versus frequency and range for sensor spacing $\rho = 12$ inches.

$\gamma > 0.99$ for range < 100 m. Is this "good"?

Curves shift up with less wind, down with more wind.
Outline

- Detection of sources
  - Saturation, $\Omega$
  - Detection performance
- Array processing
  - Coherence loss from turbulence, $\gamma$
  - Array size: 2 sensors $\rightarrow$ Source AOA
  - Array of arrays: $\rightarrow$ Source localization

- Freq. in [30, 250] Hz $\rightarrow$ $\lambda$ in [1.3, 11] m
- Angle of arrival (AOA) accuracy w.r.t.
  - Array aperture size
  - Turbulence ($\Omega$, $\gamma$)
- Small aperture:
  - Easier to deploy
  - More covert
  - Better coherence
  - How small can we go?

SenTech HE01 acoustic sensor [Prado2002]
Impact on AOA Estimation

• How does the turbulence ($\Omega$, $\gamma$) affect AOA estimation accuracy? [Sadler2004]
  – Cramer-Rao lower bound (CRB), simulated RMSE
  – Achievable accuracy with small arrays?

$$
\text{Larger sensor spacing, } \rho: \quad \text{DESIRABLE}
$$

$$
\text{BAD!}
$$

$$
\begin{align*}
\text{CRB}(\hat{\phi}) &= \frac{1}{J_{\phi \phi}}, \\
\text{CRB}(\hat{\theta}) &= \frac{\text{CRB}(\hat{\phi})}{\left(\frac{2\pi\rho}{\lambda}\right)^2 \left[1 - \left(\frac{c_o}{\rho \omega} \phi\right)^2\right]} \\
J_{\phi \phi} &= 2 \cdot \text{SNR} \left(\frac{1 - \Omega}{1 + \Omega \cdot \text{SNR}}\right) \\
&\quad \cdot \frac{1 - \Omega}{2 + \Omega \cdot \text{SNR} \left(1 - \gamma^2\right)} \\
&\quad + 2 \cdot \text{SNR} \cdot \Omega \left(\frac{1 - \Omega \left(1 - \gamma^2\right)}{\Omega \cdot \left[2 + \Omega \cdot \text{SNR} \left(1 - \gamma^2\right)\right] + \text{SNR}^{-1}}\right)
\end{align*}
$$
Special Cases of CRB

• No scattering (ideal plane wave model):

\[ J_{\phi\phi} = 2 \cdot \text{SNR} \]

SNR-limited performance

• High SNR, with scattering:

\[ J_{\phi\phi} = 2 \cdot \frac{1 - \Omega}{2\Omega + \Omega^2 \cdot \text{SNR}(1 - \gamma^2)} + 2 \cdot \frac{1 - \Omega (1 - \gamma^2)}{\Omega (1 - \gamma^2)} \]

\[ \rightarrow 2 \cdot \frac{1}{\Omega} \frac{1 - 1 + \gamma^2}{1 - \gamma^2} \]

for SNR >> 1 and \( \gamma^2 < 1 - 2/\text{SNR} \)

Coherence-limited performance

If SNR = 30 dB, then \( \gamma < 0.9989995 \) limits performance!
Phase CRB with Scattering \((\Omega, \gamma)\)

Coherence loss \(\gamma < 1\) is significant when saturation \(\Omega > 0.1\).
CRB on AOA Estimation

SNR = 30 dB for all ranges

Sensor spacing $\rho = 12$ in.

- Increasing range (fixed SNR)
  - Aperture-limited at low frequency
  - Ideal plane wave model is accurate for very short ranges $\sim 10$ m
- Coherence-limited at larger ranges

Mostly sunny, strong wind
Cloudy and Less Wind

SNR = 30 dB for all ranges

Sensor spacing $\rho = 12$ in.

Atmospheric conditions have a large impact on AOA CRBs

Aperture-limited at low frequency

Plane wave model is accurate to 100 m range
Coherence vs. Sensor Spacing

SOURCE FREQ. = 100 Hz, RANGE = 200 m, SNR = 30 dB

\[ \gamma = 0 \text{ for } \rho \sim 1,000 \text{ in} = 25 \text{ m} \]

Omega = 0.80, SUNNY
Omega = 0.43, CLOUDY

Mostly sunny, light wind
Mostly sunny, moderate wind
Mostly sunny, strong wind
Mostly cloudy, light wind
Mostly cloudy, moderate wind
Mostly cloudy, strong wind

\[ \gamma = 0 \text{ for } \rho \sim 1,000 \text{ in} = 25 \text{ m} \]
CRB on AOA vs. Sensor Spacing

SOURCE FREQ. = 100 Hz, RANGE = 200 m, SNR = 30 dB

- MOSTLY SUNNY, LIGHT WIND
- MOSTLY SUNNY, STRONG WIND
- MOSTLY CLOUDY, LIGHT WIND
- MOSTLY CLOUDY, STRONG WIND
- IDEAL PLANE WAVE (ω = 0, γ = 1)

ρ = 5 inches
Coherence vs. Sensor Spacing

SOURCE FREQ. = 100 Hz, RANGE = 1,000 m, SNR = 20 dB

Omega = 1.00, SUNNY
Omega = 0.94, CLOUDY

Mostly Sunny, Light Wind
Mostly Sunny, Moderate Wind
Mostly Sunny, Strong Wind
Mostly Cloudy, Light Wind
Mostly Cloudy, Moderate Wind
Mostly Cloudy, Strong Wind
CRB on AOA vs. Sensor Spacing

SOURCE FREQ. = 100 Hz, RANGE = 1,000 m, SNR = 20 dB

- MOSTLY SUNNY, LIGHT WIND
- MOSTLY SUNNY, STRONG WIND
- MOSTLY CLOUDY, LIGHT WIND
- MOSTLY CLOUDY, STRONG WIND
- IDEAL PLANE WAVE (Ω = 0, γ = 1)

Coherence losses degrade AOA perf. for ρ > 8 feet

Plane wave is OK for good weather

Ideal plane wave model is optimistic (poor weather)

(First noted in [Wilson1998], [Wilson1999])
Phase difference estimator:

Phase: $\hat{\phi}_{PD} = \angle z_2 - \angle z_1$

AOA: $\hat{\theta}_{PD} = \arcsin\left(\frac{c_o}{\omega \rho} \hat{\phi}_{PD}\right)$

Saturation $\Omega$ is significant for most of frequency range

Coherence is high: $\gamma > 0.999$

Scenario:
Small Sensor Spacing: $\rho = 3$ in., $\text{SNR} = 40$ dB, Range = 50 m

AOA estimators break away from CRB approx. when $\Omega > 0.1$

Turbulence prevents performance gain from larger aperture
AOA Estimation for Harmonic Source

Equal-strength harmonics at 50, 100, 150 Hz

SNR = 40 dB at 20 m range, SNR ~ 1/(range)^2 (simple TL)

Sensor spacing \( \rho = 3 \text{ in. and 6 in.} \)

Mostly sunny, moderate wind

One snapshot

Achievable AOA accuracy ~ 10’s of degrees for this case
Turbulence Conditions for Three-Harmonic Example

<table>
<thead>
<tr>
<th>Range</th>
<th>50 Hz</th>
<th>100 Hz</th>
<th>150 Hz</th>
</tr>
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<tbody>
<tr>
<td>20 m</td>
<td>0.04</td>
<td>0.15</td>
<td>0.30</td>
</tr>
<tr>
<td>100 m</td>
<td>0.18</td>
<td>0.55</td>
<td>0.84</td>
</tr>
<tr>
<td>200 m</td>
<td>0.33</td>
<td>0.80</td>
<td>0.97</td>
</tr>
</tbody>
</table>

Strong scattering

<table>
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<td>0.9998</td>
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<td>0.9999</td>
<td>0.9999</td>
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Coherence is ~ 1, but still limits performance.
Summary of AOA Estimation

- CRB analysis of AOA estimation
  - Tradeoff: larger aperture vs. coherence loss
  - Ideal plane wave model is overly optimistic for longer source ranges
  - Performance varies significantly with weather cond.
  - Important to consider turbulence effects

- AOA algorithms do not achieve the CRB in turbulence ($\Omega > 0.1$) with one snapshot

- Similar results obtained for circular arrays with > 2 sensors [Sadler2004]
Outline

- Detection of sources
  - Saturation, $\Omega$
  - Detection performance
- Array processing
  - Coherence loss from turbulence, $\gamma$
  - Array size: 2 sensors → Source AOA
  - Array of arrays: → Source localization

Triangulation/TDOA, minimize comms.

- Issues:
  - Comm. bandwidth
  - Distributed processing
  - Exploit long baselines?
  - Time sync. among arrays
- Model assumptions:
  - Individual arrays:
    * Perfect coherence
    * Far-field
  - Between arrays:
    * Partial coherence
    * Different power spectra
    * Near-field
Three Localization Schemes

1) Triangulate AOAs:
- Comms.: Low
- Distributed processing
- Coarse time sync.

2) Fully centralized
- Comms.: High
- Centralized processing
- Fine time sync. req’d
- Near-field w.r.t. arrays

3) AOAs & TDOAs:
- Comms.: Medium
- Distributed processing
- Fine time sync. req’d
- Alt.: Each array xmits raw data from 1 sensor

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Localization Cramer-Rao Bounds [Kozick2004b]

1. Triangulation of AOAs  
   Minimal comms.
2. Fully centralized  
   Maximum comms.
3. #1 + time delay estimation (TDE)  
   Raw data from 1 sensor

- Schemes 2 & 3 have same CRB!
- Results are coherence sensitive: coherence improves CRB over AOA triangulation
- Are the CRBs achievable?

Parameters:
- 3 arrays, 7 elements, 8 ft. diam.
- Narrowband (49.5 to 50.5 Hz)
- SNR = 16 dB at each sensor
- 0.5 sec. observation time
Ziv-Zakai Bound on TDE

Threshold coherence to attain CRB:

- Function(SNR, % BW, TB product, coherence)
- Extends [WeissWeinstein83] to TDE with partially-coherent signals

\[ |\gamma_s|^2 \geq \left( 1 + \frac{1}{(G_s/G_w)} \right)^2 \]

\[ \text{SNR}_{\text{thresh}} = \frac{6}{\pi^2} \left( \frac{\Delta \omega T}{2\pi} \right)^2 \left( \frac{\omega_0}{\Delta \omega} \right)^2 \left[ \phi^{-1} \left( \frac{1}{24} \left( \frac{\Delta \omega}{\omega_0} \right)^2 \right) \right]^2 \]

\[ \phi(y) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} \exp(-t^2/2) \, dt \]
Threshold Coherence Simulation

RMS TDE (WIDEBAND): $f_0 = 100$ Hz, $\Delta f = 30$ Hz

RMS TDE (NARROWBAND): $f_0 = 40$ Hz, $\Delta f = 2$ Hz

THRESHOLD COHERENCE = 0.41

THRESHOLD COHERENCE > 1.0

Breakaway from CRB is accurately predicted by threshold coherence value
Threshold Coherence

Narrowband source requires perfect coherence

Doubling fractional BW ⇒ time-BW product reduced by factor of ~ 10

\( f_0 = 50 \text{ Hz}, \Delta f = 5 \text{ Hz} \Rightarrow T > 100 \text{ s} \)
TDE Experiment – Harmonic Source

MEAN SHORT-TIME SPECTRAL COHERENCE, ARRAYS 1 & 3

- Moderate coherence, small bandwidth

- TDE is not possible between arrays

TDE works within an array (sensor spacing < 8 feet)
TDE Experiment – Wideband Source

Measured coherence exceeds threshold
coherence ~ 0.8 for this case

Accurate localization from TDEs
Summary of Array of Arrays

- Threshold coherence analysis tells conditions when joint, coherent processing improves localization accuracy.
- Pairwise TDE between arrays captures localization information ➔ reduced comms.
- Incoherent triangulation of AOAs is optimum for narrowband, harmonic sources.
Odds & Ends
Other Sensing Approaches

• Infrasonics: $f < 30 \text{ Hz}, \lambda > 11 \text{ m}$ [Bedard2000]
  – Over the horizon propagation via ducting from temperature gradients
  – Wind noise is very high
  – Propagation models may be lacking

• Fuse acoustics with other low-BW sensor modalities
  – Seismic has proven useful for heavy, loud vehicles and aircraft (also footsteps)
  – Vector magnetic sensors are emerging
Odds & Ends
Other Processing

• Doppler estimation: [Kozick2004c]
  – Localize based on differential Doppler from multiple sensors (combine with AOAs?)
  – Not sensitive to coherence
  – Simple, and exploits spectral lines in source
  – We have analyzed CRBs and algorithms

• Tracking of moving sources [see Biblio.]

• Classification based on harmonic ampls. [see Biblio.]
  – Harmonic amplitudes fluctuate
  – Exploit aspect angle differences of sources?
Summary

- **Source characteristics:**
  - Spectral lines, ultra-wideband, high SNR
- **Propagation:** dominated by turbulent scattering
  - Amplitude & phase fluctuations (saturation, $\Omega$)
  - Spatial coherence loss (coherence, $\gamma$)
  - Depends on freq., range, weather, sensor spacing
- **Signal processing:**
  - Coherence losses limit AOA and TDE performance
    - Ideal plane wave is overly optimistic
  - Implications for detection and array aperture size
  - Sensor network: comms. & distributed processing

Provided a detailed case-study of a particular sensor network.