

“Stochastic Signal” Gaussian Model

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Lecture 26

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A Stochastic Gaussian Model

- N sources in additive noise

$$\underline{\mathbf{y}}(l) = \sum_{n=1}^{N_s} \mathbf{e}(\boldsymbol{\theta}_n) \underline{s}_n(l) + \underline{\mathbf{n}}(l)$$

$$\underline{\mathbf{n}} \sim CN(0, \mathbf{K}_n)$$

$$\underline{\mathbf{s}} = \begin{bmatrix} \underline{s}_1 \\ \vdots \\ \underline{s}_{N_s} \end{bmatrix} \sim CN(0, \mathbf{K}_s)$$



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Uncorrelated Sources

- Sources may be uncorrelated (usual model we've used in class)...

$$\mathbf{K}_s = \begin{bmatrix} \sigma_1^2 & 0 & \cdots & 0 \\ 0 & \sigma_2^2 & & 0 \\ \vdots & & \ddots & \vdots \\ 0 & 0 & \cdots & \sigma_{N_s}^2 \end{bmatrix}$$

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Correlated Sources

- Or they may be correlated (for instance, due to multipath)

$$\mathbf{K}_s = \begin{bmatrix} \sigma_1^2 & c_{12} \sigma_1 \sigma_2 & \cdots & c_{1N_s} \sigma_1 \sigma_{N_s} \\ c_{12}^* \sigma_1 \sigma_2 & \sigma_2^2 & & c_{2N_s} \sigma_2 \sigma_{N_s} \\ \vdots & & \ddots & \vdots \\ c_{1N_s}^* \sigma_1 \sigma_{N_s} & c_{2N_s}^* \sigma_2 \sigma_{N_s} & \cdots & \sigma_{N_s}^2 \end{bmatrix}$$

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Fun Fact from Probability

- **Independent** \Rightarrow **uncorrelated**
- **Uncorrelated** $\not\Rightarrow$ **independent**
(in general)
- **Uncorrelated+Gaussian**
 \Rightarrow **independent**



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Distribution of the Data

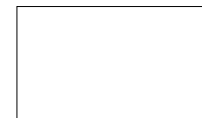
- N sources in additive noise

$$\underline{\mathbf{y}} \sim CN(0, \mathbf{K}_y)$$

$$\mathbf{K}_y = \mathbf{D}(\Theta) \mathbf{K}_s \mathbf{D}^H(\Theta) + \mathbf{K}_n$$

$$\mathbf{D}(\Theta) = \begin{bmatrix} \mathbf{e}(\theta_1) & \cdots & \mathbf{e}(\theta_{N_s}) \end{bmatrix}$$

$$\Theta = \begin{bmatrix} \theta_1 & \cdots & \theta_{N_s} \end{bmatrix}$$



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Data Covariance (1)

$$\underline{\mathbf{y}}(l) = \mathbf{D}(\Theta) \underline{\mathbf{s}}(l) + \underline{\mathbf{n}}(l)$$

$$\mathbf{K}_y = E[\underline{\mathbf{y}} \underline{\mathbf{y}}^H]$$

$$= E[\{\mathbf{D}(\Theta) \underline{\mathbf{s}} + \underline{\mathbf{n}}\} \{\mathbf{D}(\Theta) \underline{\mathbf{s}} + \underline{\mathbf{n}}\}^H]$$

$$= E[\mathbf{D}(\Theta) \underline{\mathbf{s}} \underline{\mathbf{s}}^H \mathbf{D}^H(\Theta)] + E[\underline{\mathbf{n}} \underline{\mathbf{n}}^H]$$

$$+ E[\mathbf{D}(\Theta) \underline{\mathbf{s}} \underline{\mathbf{n}}^H] + E[\underline{\mathbf{n}} \underline{\mathbf{s}}^H \mathbf{D}^H(\Theta)]$$

$$= E[\mathbf{D}(\Theta) \underline{\mathbf{s}} \underline{\mathbf{s}}^H \mathbf{D}^H(\Theta)] + E[\underline{\mathbf{n}} \underline{\mathbf{n}}^H]$$



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Data Covariance (2)

$$\mathbf{K}_y = E[\mathbf{D}(\Theta) \underline{\mathbf{s}} \underline{\mathbf{s}}^H \mathbf{D}^H(\Theta)] + E[\underline{\mathbf{n}} \underline{\mathbf{n}}^H]$$

$$= \mathbf{D}(\Theta) E[\underline{\mathbf{s}} \underline{\mathbf{s}}^H] \mathbf{D}^H(\Theta) + E[\underline{\mathbf{n}} \underline{\mathbf{n}}^H]$$

$$= \mathbf{D}(\Theta) \mathbf{K}_s \mathbf{D}^H(\Theta) + \mathbf{K}_n$$



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Probability Density of the Data

$$\underline{\mathbf{y}} \sim CN(0, \mathbf{K}_y)$$

- **Circular (Goodman) zero-mean Gaussian density for L independent snapshots:** $p(\mathbf{y}) =$

$$\frac{1}{(\pi^M \det \mathbf{K}_y)^L} \exp \left[- \sum_{l=0}^{L-1} \mathbf{y}^H(l) \mathbf{K}_y^{-1} \mathbf{y}(l) \right]$$

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Loglikelihood Calculation

- **Loglikelihood** $\ln p(\mathbf{y}) =$

$$- \cancel{LM} \ln \pi - L \ln \det \mathbf{K}_y - \sum_{l=0}^{L-1} \mathbf{y}^H(l) \mathbf{K}_y^{-1} \mathbf{y}(l)$$

$$L \operatorname{tr} \left[\frac{1}{L} \sum_{l=0}^{L-1} \mathbf{y}^H(l) \mathbf{K}_y^{-1} \mathbf{y}(l) \right]$$

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Trace Rearrangement Trick

$$\begin{aligned} & \operatorname{tr} \left[\frac{1}{L} \sum_{l=0}^{L-1} \mathbf{y}^H(l) \mathbf{K}_y^{-1} \mathbf{y}(l) \right] \\ &= \frac{1}{L} \sum_{l=0}^{L-1} \operatorname{tr} \left[\mathbf{y}^H(l) \mathbf{K}_y^{-1} \mathbf{y}(l) \right] \\ &= \operatorname{tr} \left[\underbrace{\frac{1}{L} \sum_{l=0}^{L-1} \mathbf{y}(l) \mathbf{y}^H(l) \mathbf{K}_y^{-1}}_{\hat{\mathbf{K}}_y} \right] = \operatorname{tr} \left[\hat{\mathbf{K}}_y \mathbf{K}_y^{-1} \right] \end{aligned}$$

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Maximum-Likelihood Estimation

- **Goal: maximize**

$$-L \ln \det \mathbf{K}_y(\xi) - L \operatorname{tr} \left[\hat{\mathbf{K}}_y \mathbf{K}_y^{-1}(\xi) \right]$$

where

$$\mathbf{K}_y(\xi) = \mathbf{D}(\Theta) \mathbf{K}_s \mathbf{D}^H(\Theta) + \mathbf{K}_n$$

over ξ , which represents all the parameters (angles, signal powers, correlation coefficients)

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Important Caveat

- The maximization must be over the feasible set, i.e. $\mathbf{K}_y(\xi)$ must be a legitimate covariance matrix (nonnegative definite)

- To make sense at all, we need

$$\dim(\xi) \leq M^2$$

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How Can We Maximize?

- No closed form solution in general
- Still an open research problem!
- One approach: try an **expectation-maximization** algorithm (sometimes ECE7251 covers EM algorithms)

M.I. Miller and D.R. Fuhrmann, "Maximum-Likelihood Narrow-Band Direction Finding and the EM Algorithm," *IEEE Trans. ASSP*, 38 (9), Sept. 1990, pp. 1560-1577.

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Adding More Detail

- Could extend model with:
 - Unknown noise covariance, for instance

$$\mathbf{K}_n = \mathbf{I} \underbrace{\sigma_n^2}_{\text{Make a parameter}}$$

- Uncertainties in sensor positions

$$\mathbf{x} = \bar{\mathbf{x}} + \underbrace{\delta \mathbf{x}}_{\text{Make a parameter}}$$

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Alternative: Least Squares Hack

- Find feasible parameter ξ that minimizes

$$\left\| \hat{\mathbf{K}}_y - \mathbf{K}_y(\xi) \right\|^2$$

- **Nonlinear Least Squares problem**
 - Large literature on numerical techniques
 - Can use MATLAB Optimization Toolbox
- **Discussed in Sec. 7.1.2 of J&D**

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