A New Theory, Techniques and Alternatives for Direction-of-Arrival Estimation in Acoustic Signal Processing

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Presentation Outline

1. Introduction: Preliminary Assessment, Objective, and New Approaches
2. Research #1: Acoustic DOA Estimation by using Theory of Orthogonal Procrustes Analysis
3. Research #2: Extension Theory of Orthogonal Procrustes Analysis for Acoustic DOA Estimation
4. Research #3: Acoustic DOA and Variance Estimation via Complex-Valued Tensor Factorization
5. Summary: Conclusions

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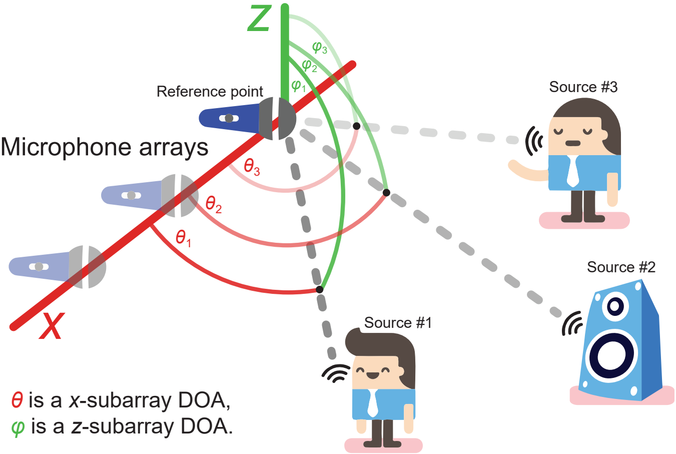
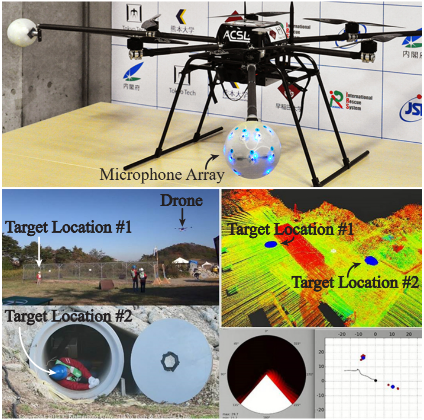
Introduction: Direction-of-Arrival in the Field of Acoustics



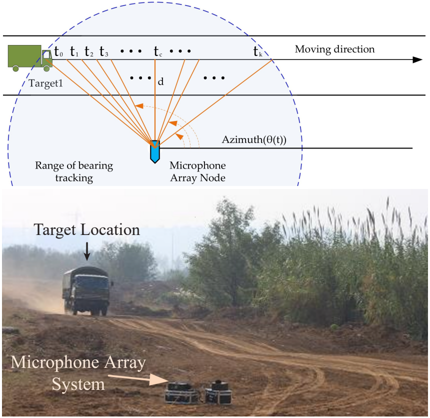
Usages of acoustic Direction-of-Arrival (DOA) estimation

- Speech enhancement, source separation, human computer interaction
- Other applications; surveillance, automatic camera management

Introduction: Examples of the Applications



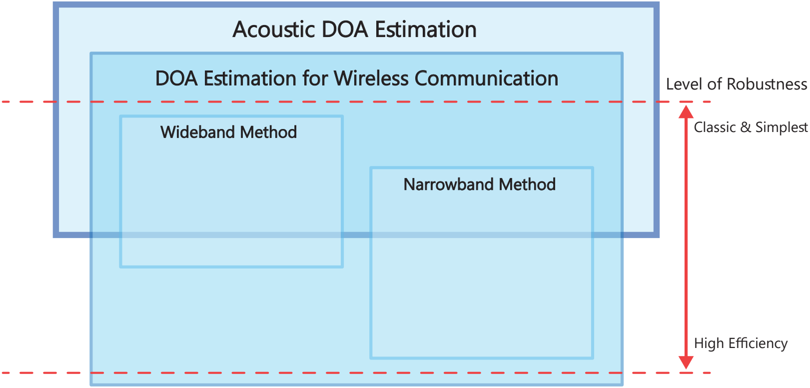
Reference:
Satoshi Tadokoro. (2017, December 25) Impulsing Paradigm Change through Disruptive Technologies Program (ImPACT): Tough Robotics Challenge. Retrieved from http://www.jst.go.jp/impact/en/program/07.html.



Reference:
Liu, Huawei; Li, Baoqing; Yuan, Xiaobing; Zhou, Qianwei; Huang, Jingchang. 2018. "A Robust Real Time Direction-of-Arrival Estimation Method for Sequential Movement Events of Vehicles." Sensors 18, no. 4: 992.

Introduction: Preliminary Assessment

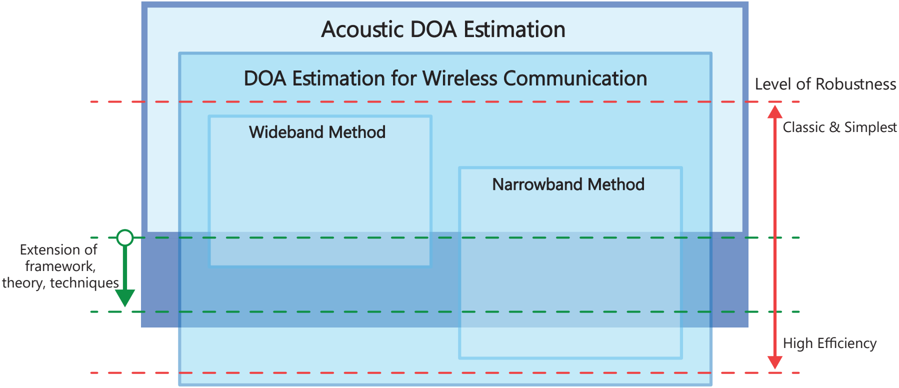
- **Discussion**: The existing framework of acoustic DOA estimation



- **Problem**: **Lack of high efficient techniques** and suitable theory when it comes to the acoustic DOA estimation

Introduction: Preliminary Assessment

- **Discussion**: The existing framework of acoustic DOA estimation



- **Solution**: **Propose a new theory** to extend the existing framework form wireless communication field to acoustic signal processing

Introduction: Research Objective and Contribution

- **To propose an alternative theory for acoustic DOA estimation**; this theory enables some useful techniques in wireless communication field to implement an acoustic DOA estimation for reducing a computational complexity and facilitating the estimation algorithm.

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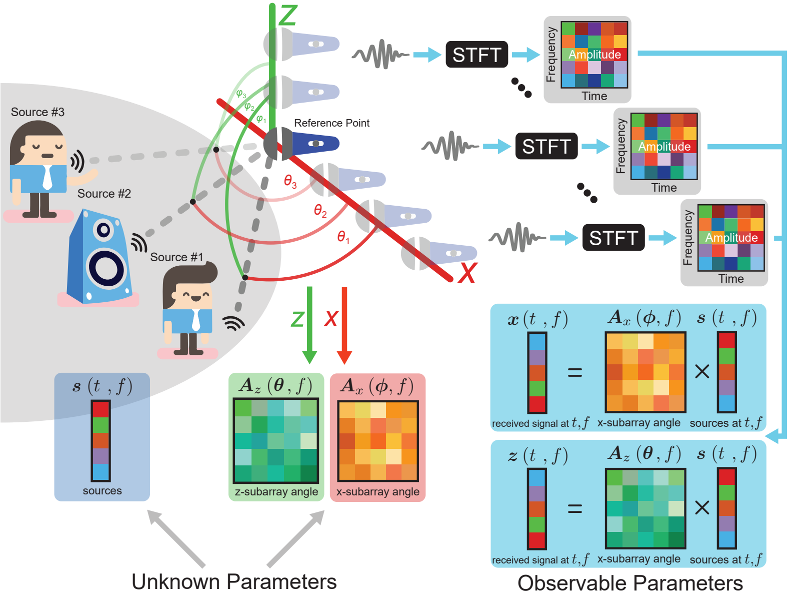
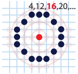
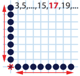
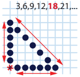
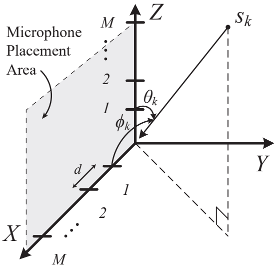
Research #1: System Overviews



Cramer-Rao bound (CRB)

Structure	Figure	CRB
Octagon Array (Circle Array)		$\frac{57}{\delta M^3}$
L-Shaped Array		$\frac{60}{\delta M^3}$
Cross Array		$\frac{96}{\delta M^3}$
Triangle Array		$\frac{108}{\delta M^3}$

$\delta = 2\text{SNR}\left(\frac{2\pi d}{\lambda}\right)^2$, CRB represents the lowest error bound of DOA.



Structure	Figure	CRB
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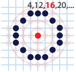
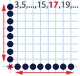
Octagon Array (Circle Array)		$\frac{57}{\delta M^3}$
L-Shaped Array		$\frac{60}{\delta M^3}$
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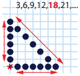
Triangle Array		$\frac{108}{\delta M^3}$

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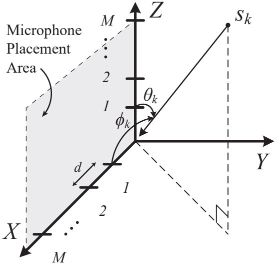
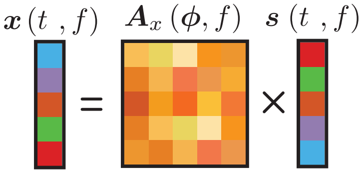


- Octagon CRB has only 5% smaller than L-Shaped CRB.
- DOA for L-Shaped array is widely proposed recently. (more DOA technique)

 Y. Hua *et al.*, "L-shaped for estimating 2D DOA," IEEE, 1991.

Signal Model at X-axis :



signals received by the microphone array

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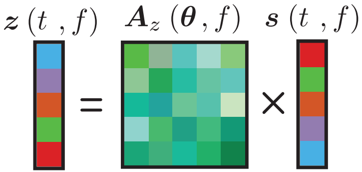
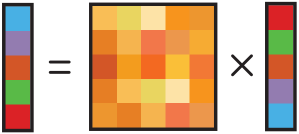


signals received by the microphone array

Research #1: General Model via Cross-Correlation

Signal Model at X-axis :

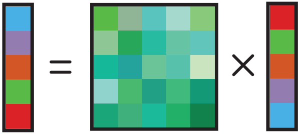
$$\boldsymbol{x}(t\ ,f) \quad \boldsymbol{A}_x(\phi, f) \quad \boldsymbol{s}(t\ ,f)$$



signals received by the microphone array

Signal Model at Z-axis :

$$\boldsymbol{z}(t\ ,f) \quad \boldsymbol{A}_z(\boldsymbol{\theta}, f) \quad \boldsymbol{s}(t\ ,f)$$

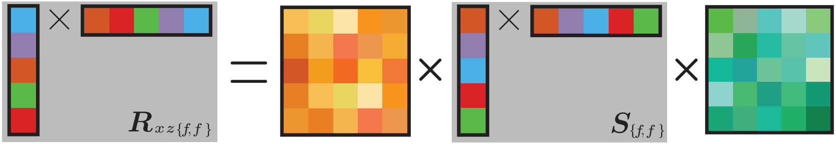


signals received by the microphone array

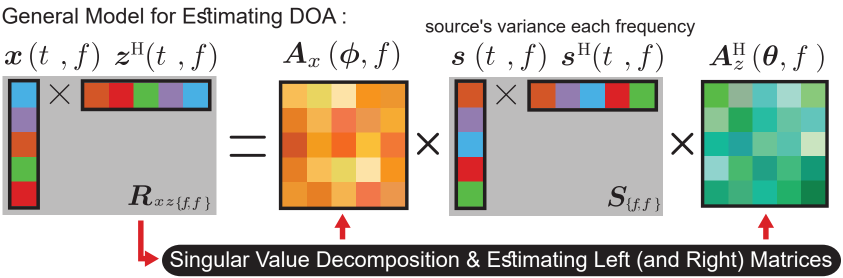
General Model for Estimating DOA :

source's variance each frequency

$$\boldsymbol{x}(t\ ,f)\ \boldsymbol{z}^{\mathrm{H}}(t\ ,f) \quad \boldsymbol{A}_x(\phi, f) \quad \boldsymbol{s}(t\ ,f)\ \boldsymbol{s}^{\mathrm{H}}(t\ ,f) \quad \boldsymbol{A}_z^{\mathrm{H}}(\boldsymbol{\theta}, f\ )$$



Research #1: Well-known Direction-of-Arrival Methods



Well-known methods for estimating subarray angles:

- Multiple Signal Classification (MUSIC) [R.Schmidt, 1986]
- Estimation of Signal Parameters via Rotational Invariance Techniques (ESPRIT) [R.Roy *et al.*, 1989]
- 2-dimensional MUSIC [M.G.Porozantzidou *et al.*, 2010]

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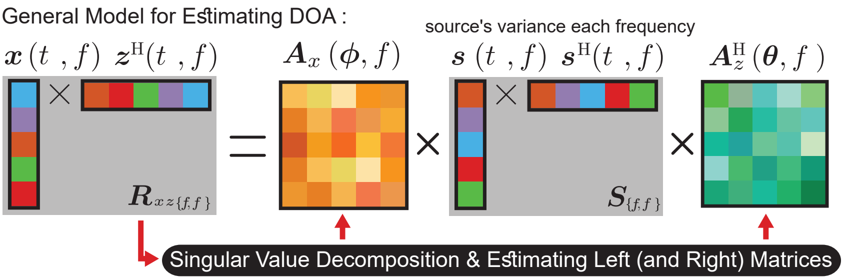

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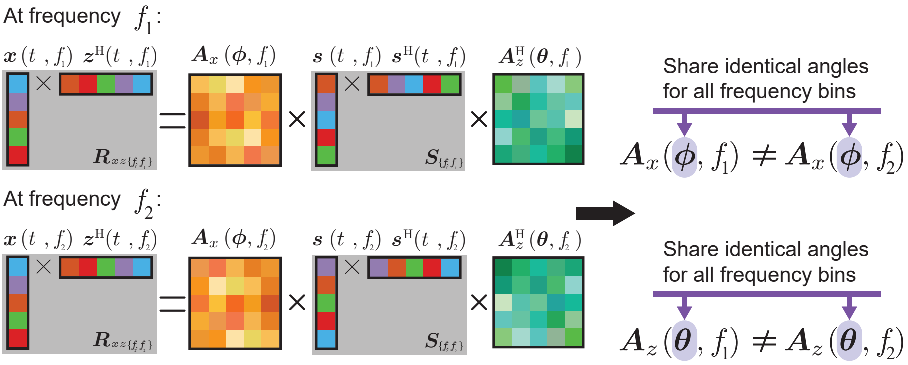
- These methods hold great promise in high efficient DOA method
- It is impossible to directly apply in human voice (multiple frequency)

Research #1: Angle Matrices on Wide Frequency Range



- Sources always have various frequency ranges; music, human voice

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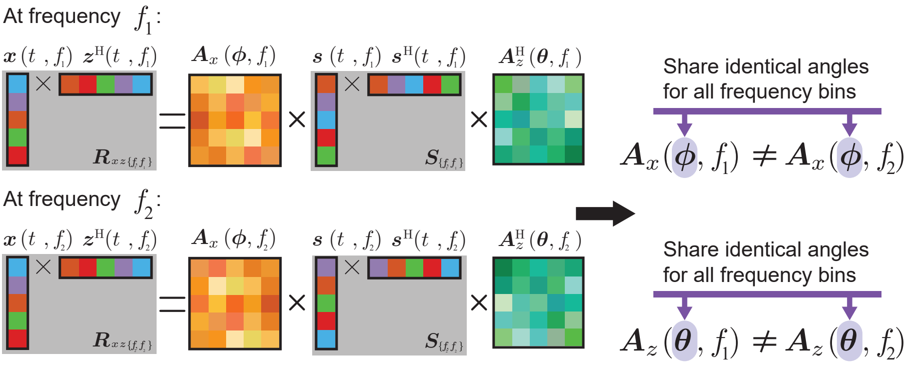
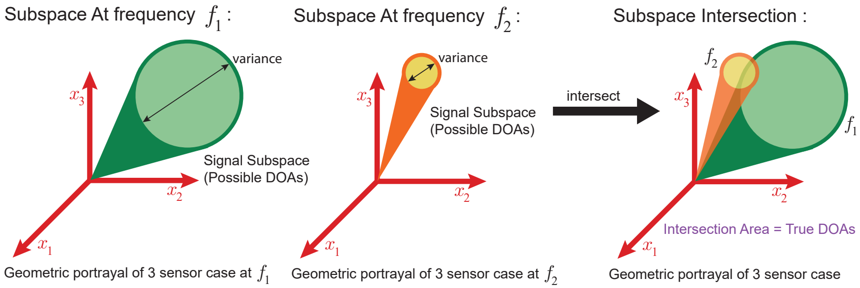


- Sources always have various frequency ranges; music, human voice
- The left & right matrices are differences for all frequency bins
- However, they share same angles for all frequency bins

Research #1: Problem of Multiple Subspace



- Signal subspace area represent the possibility of true DOAs

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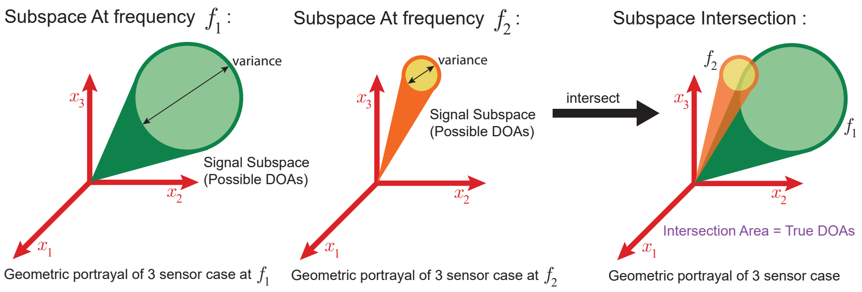

- Signal subspace area represent the possibility of true DOAs
- DOAs can be determined by intersecting the area between f_1 and f_2
- When there is no intersection area, it is impossible to detect DOAs

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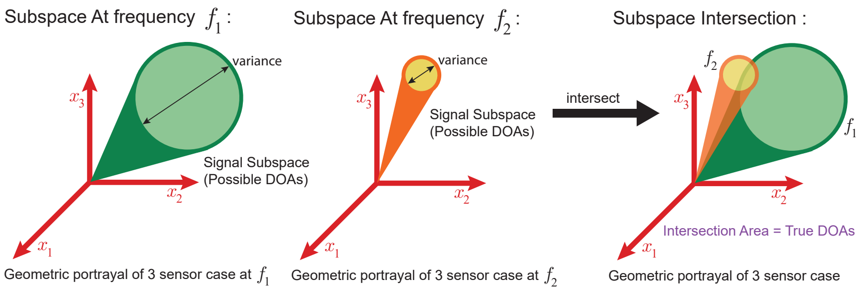
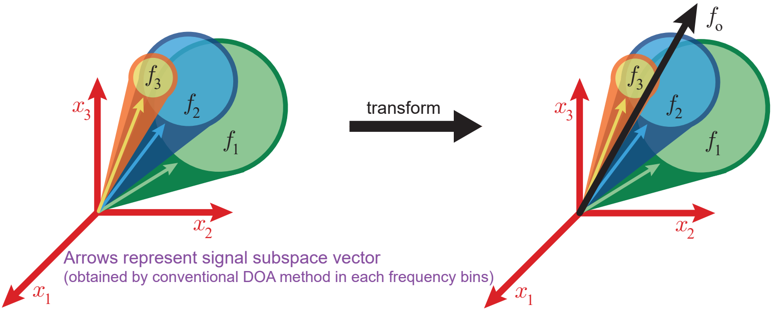


- Signal subspace area represent the possibility of true DOAs
- DOAs can be determined by intersecting the area between f_1 and f_2
- When there is no intersection area, it is impossible to detect DOAs

- Employing conventional DOA estimation in each frequency bins cannot obtain this intersection area

Research #1: Problem of Multiple Subspace

Subspace Intersection : Subspace Transformation (all frequency bins) :



Geometric portrayal of 3 sensor case

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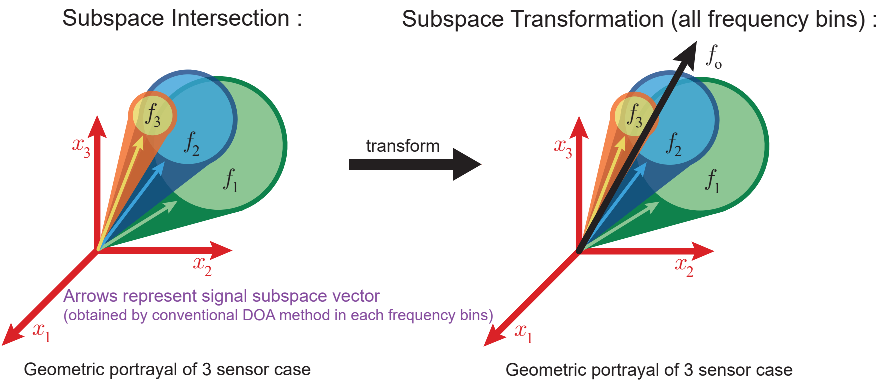
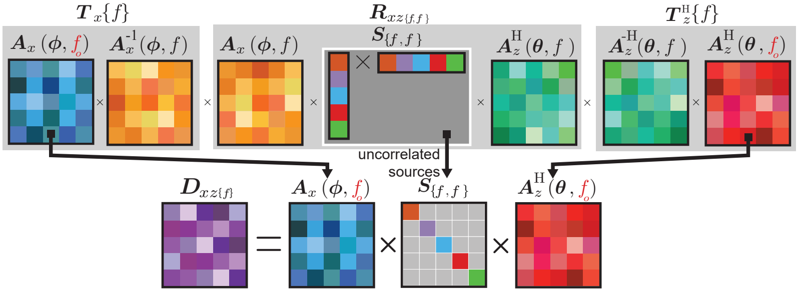
- **Problem**: How to get the center of intersection area (or signal subspace vector at f_o) without employing the intersection area?

Research #1: Problem of Multiple Subspace



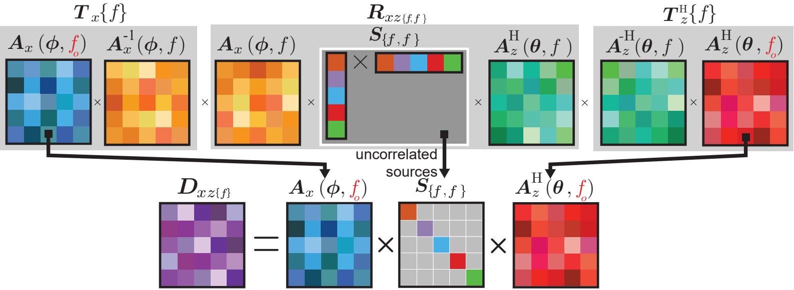
- **Problem**: How to get the center of intersection area (or signal subspace vector at f_o) without employing the intersection area?
- **Solution**: Subspace transformation for all frequency bins

Research #1: Subspace Transformation Process



- $\boldsymbol{A}_x(\phi, f_o) = \boldsymbol{T}_{x\{f\}}\boldsymbol{A}_x(\phi, f), \quad \boldsymbol{A}_z(\boldsymbol{\theta}, f_o) = \boldsymbol{T}_{z\{f\}}\boldsymbol{A}_z(\boldsymbol{\theta}, f), \quad \forall f.$

Research #1: Subspace Transformation Process



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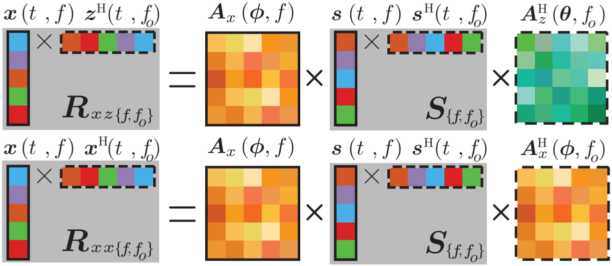
Optimization Problem for Estimating $\boldsymbol{T}_{x\{f\}}$, $\boldsymbol{T}_{z\{f\}}$ (impracticable!)

$$\underset{\boldsymbol{T}_{x\{f\}}}{\text{minimize}} \quad \left\| \boldsymbol{A}_x(\phi, f_o) - \boldsymbol{T}_{x\{f\}}\boldsymbol{A}_x(\phi, f) \right\|_{\mathrm{F}}^2 ,$$

$$\underset{\boldsymbol{T}_{z\{f\}}}{\text{minimize}} \quad \left\| \boldsymbol{A}_z(\theta, f_o) - \boldsymbol{T}_{z\{f\}}\boldsymbol{A}_z(\theta, f) \right\|_{\mathrm{F}}^2 .$$

Research #1: Possible Solution for Estimating $\boldsymbol{T}_{x\{f\}}$

New Model for Estimating $\boldsymbol{T}_{x\{f\}}$:



- Matrices above are valid iff $x(t, f), z(t, f)$ are not a stationary signal

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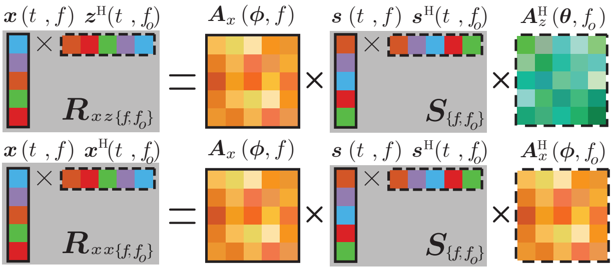

- Matrices above are valid iff $x(t, f), z(t, f)$ are not a stationary signal

Practical Optimization Problem for Estimating $\boldsymbol{T}_{x\{f\}}$

$$\underset{\boldsymbol{T}_{x\{f\}}}{\text{minimize}} \quad \left\| \boldsymbol{R}_{xz\{f_o,f_o\}} - \boldsymbol{T}_{x\{f\}} \boldsymbol{R}_{xz\{f,f_o\}} \right\|_{\mathrm{F}}^2 ,$$

$$\underset{\boldsymbol{T}_{x\{f\}}}{\text{minimize}} \quad \left\| \boldsymbol{R}_{xx\{f_o,f_o\}} - \boldsymbol{T}_{x\{f\}} \boldsymbol{R}_{xx\{f,f_o\}} \right\|_{\mathrm{F}}^2 .$$

Research #1: Solution for Estimating $\boldsymbol{T}_{x\{f\}}$, $\boldsymbol{T}_{z\{f\}}$

Given a temporal frequency f, the solution matrices are defined as:

$$\boldsymbol{\Psi}_{x\{f\}} = \boldsymbol{R}_{xz\{f,f_\mathrm{o}\}}\boldsymbol{R}^{\mathrm{H}}_{xz\{f_\mathrm{o},f_\mathrm{o}\}},$$
$$\boldsymbol{\Psi}_{z\{f\}} = \boldsymbol{R}_{zx\{f,f_\mathrm{o}\}}\boldsymbol{R}^{\mathrm{H}}_{zx\{f_\mathrm{o},f_\mathrm{o}\}},$$

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Theorem: Orthogonal Procrustes Analysis

The one possible solution of the optimization problems are given as:

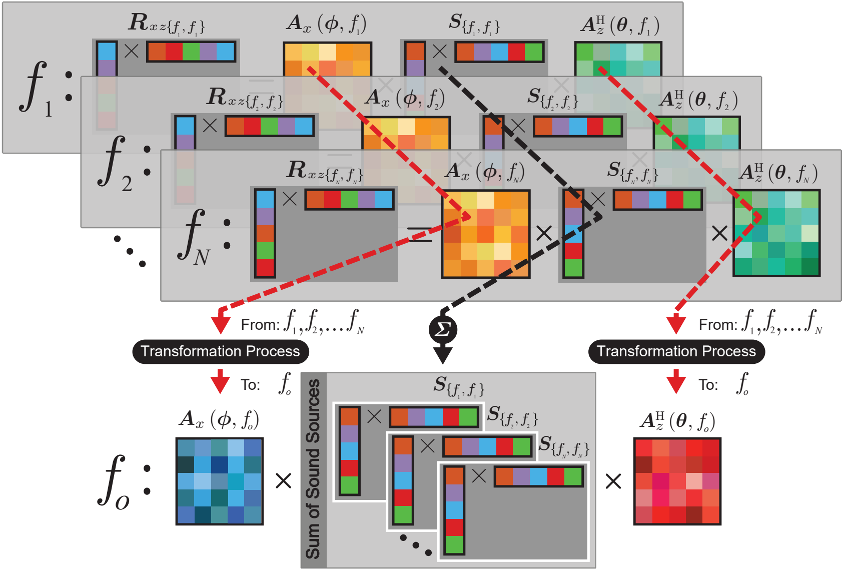
$$\boldsymbol{T}_{x\{f\}} = \boldsymbol{V}_{x_s\{f\}}\boldsymbol{U}^{\mathrm{H}}_{x_s\{f\}},$$

$$\boldsymbol{T}_{z\{f\}} = \boldsymbol{V}_{z_s\{f\}}\boldsymbol{U}^{\mathrm{H}}_{z_s\{f\}},$$

where $\boldsymbol{\Psi}_{x\{f\}}$, $\boldsymbol{\Psi}_{z\{f\}}$ are factorized via Singular-Value Decomposition;

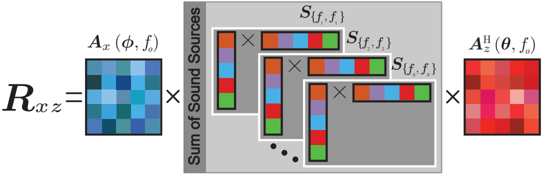
$$\boldsymbol{\Psi}_{x\{f\}} = \boldsymbol{U}_{x_s\{f\}}\boldsymbol{\Sigma}_{x_s\{f\}}\boldsymbol{V}^{\mathrm{H}}_{x_s\{f\}} + \boldsymbol{U}_{x_w\{f\}}\boldsymbol{\Sigma}_{x_w\{f\}}\boldsymbol{V}^{\mathrm{H}}_{x_w\{f\}},$$
$$\boldsymbol{\Psi}_{z\{f\}} = \boldsymbol{U}_{z_s\{f\}}\boldsymbol{\Sigma}_{z_s\{f\}}\boldsymbol{V}^{\mathrm{H}}_{z_s\{f\}} + \boldsymbol{U}_{z_w\{f\}}\boldsymbol{\Sigma}_{z_w\{f\}}\boldsymbol{V}^{\mathrm{H}}_{z_w\{f\}}.$$

Research #1: Solution for Estimating $T_{x\{f\}}, T_{z\{f\}}$



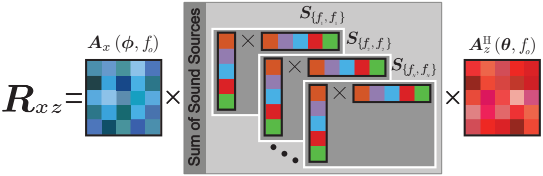
The above components can be referred to as singular values

Research #1: New Framework for Estimating DOA



- Employ SVD in each frequency bins
- Transform all f into f_o space
- $\boldsymbol{R}_{xz}$ is now able to perform SVD; it is compatible with recent subspace methods.

Research #1: New Framework for Estimating DOA



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- Transform all f into f_o space
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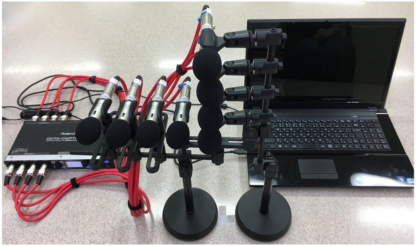
DOA Estimation Steps:

1. Obtain $\boldsymbol{T}_{x\{f\}}$, $\boldsymbol{T}_{z\{f\}}$
2. Calculate $\boldsymbol{R}_{xz}$
3. Performing SVD of $\boldsymbol{R}_{xz} = \boldsymbol{U}\boldsymbol{\Sigma}\boldsymbol{V}^{\mathrm{H}}$
4. Estimate DOA angles
   $\boldsymbol{U} \equiv \boldsymbol{A}_x(\phi, f_o)$
   $\boldsymbol{V} \equiv \boldsymbol{A}_z(\theta, f_o)$
   (X. Nie *et al.*, 2015)
   - Possible to change another method

X. Nie *et al.*, "Array aperture extension algorithm for 2-d doa estimation with l-shaped array," 2015.

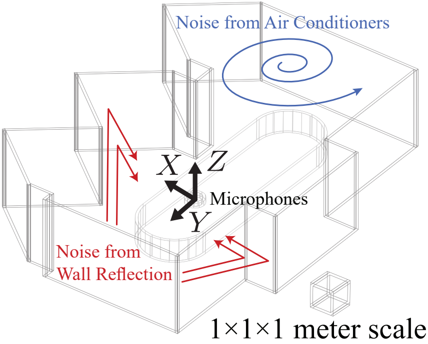
Research #1: Experimentation

- Experiment Setup :



- Number of Microphone : 8
- Capture time : 5 second
- Reverberation time : 0.3 second
- SNR value : 22.78 dB
- Focus only front direction

- Room Dimensions :



- KUT meeting room (A511)
- 2 - 3 People speak to the microphones simultaneity

Research #1: Experimental Result

- Performance under the real environment
- Azimuth (ψ) and elevation (or zenith, θ) angles are considered
- $\cos\phi_k = \sin\theta_k \cos\psi_k$

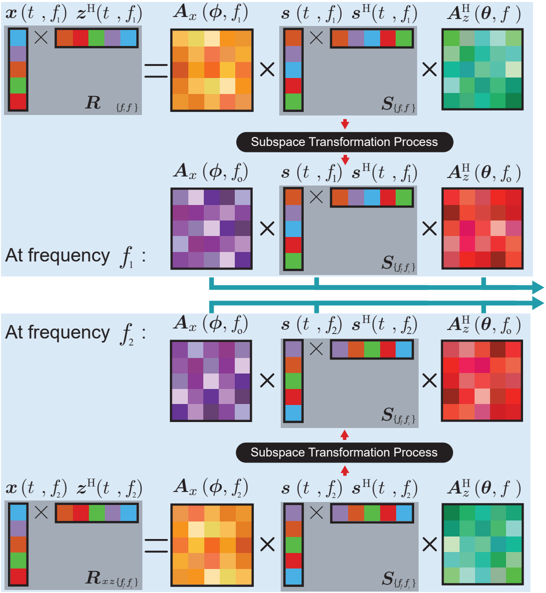
Incident Sources			Average of Calculated DOAs (Degree)			
Number	Position	Angle (Degree)	IMUSIC	TOFS	CSS-PGAM	Proposed Method
2	ψ_1	45.000	58.292	**57.231**	60.276	57.877
	θ_1	50.000	56.207	55.119	53.537	**50.140**
	ψ_2	135.000	**139.610**	142.596	*failed*	152.335
	θ_2	100.000	91.673	91.788	*failed*	**99.245**
3	ψ_1	45.000	*failed*	*failed*	57.489	**49.943**
	θ_1	55.000	*failed*	*failed*	**57.079**	48.291
	ψ_2	100.000	*failed*	*failed*	97.312	**98.575**
	θ_2	95.000	*failed*	*failed*	93.189	**93.505**
	ψ_3	135.000	**140.857**	141.631	*failed*	149.198
	θ_3	135.000	93.449	94.939	*failed*	**119.271**

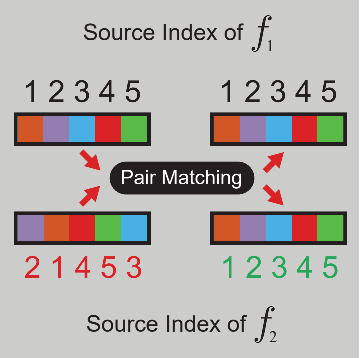
Research #1: References

- [IMUSIC] G. Su *et al.*, "The signal subspace approach for multiple wide-band emitter location," 1983.
- [TOFS] H. Yu *et al.*, "A new method for wideband doa estimation," 2007.
- [CSS-PGAM] B. Suksiri *et al.*, "A computationally efficient wideband direction-of-arrival estimation method for l-shaped microphone arrays," 2018.

Presentation Outline

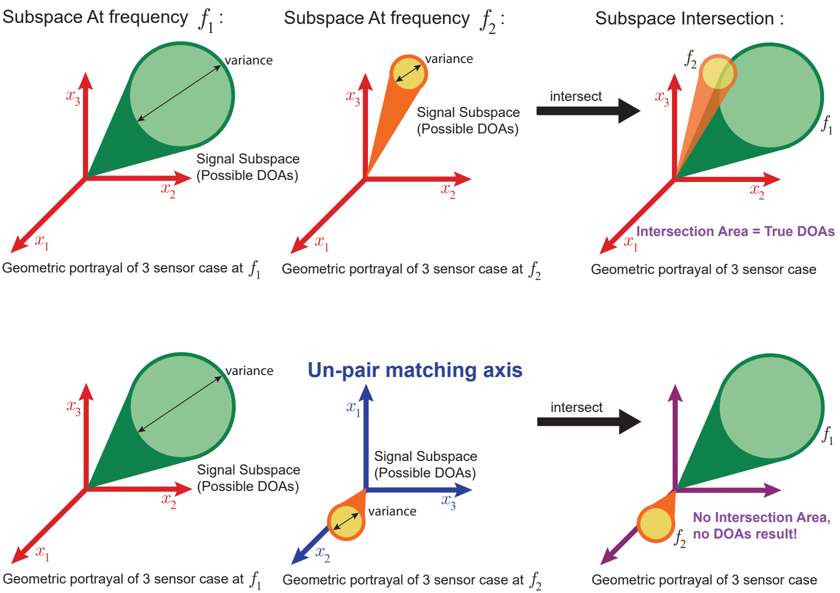
Research #2: Problem with Previously Version





- Index have to be arranged correctly
- Pair matching technique between the temporal space is required

Research #2: Problem with Previously Version



Research #2: Possible Solution

- **Discussion**: Why Did This Happen?

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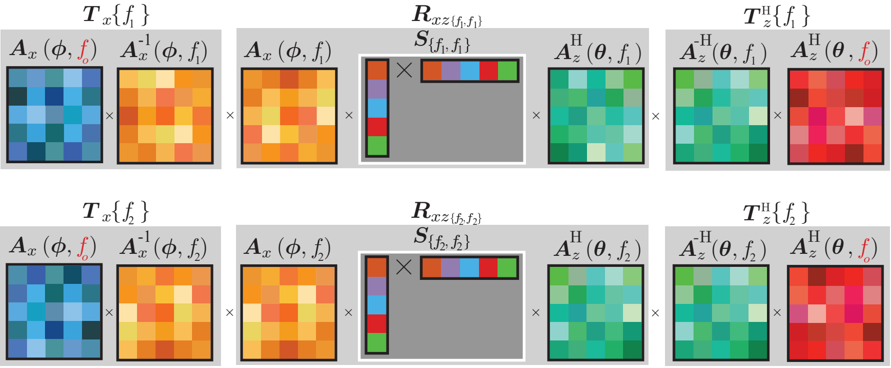

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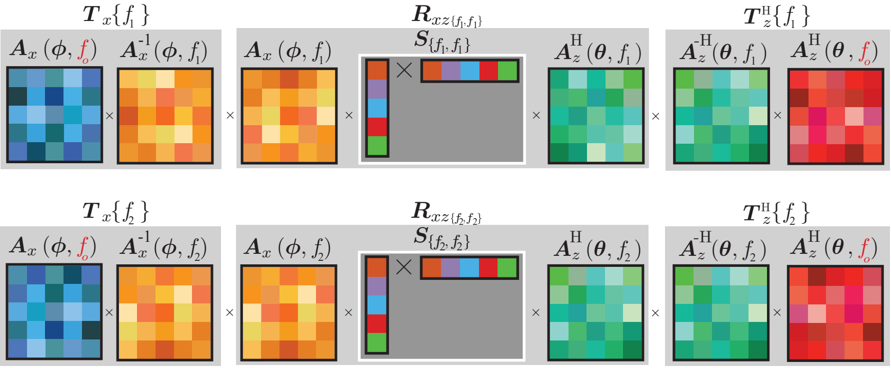

- **Solution**: $\boldsymbol{T}_{x\{f_1\}}, \boldsymbol{T}_{x\{f_2\}}, \cdots$ have to be estimated simultaneously

Research #2: New Solution for Estimating $\boldsymbol{T}_{x\{f\}}$ via $\boldsymbol{R}_{xz}$

New Optimization Problem for Estimating $\boldsymbol{T}_{x\{f\}}$ via $\boldsymbol{R}_{xz}$

$$\begin{aligned}
\underset{\boldsymbol{T}_{x\{f\}}}{\text{minimize}} \quad & \left\| \boldsymbol{R}_{xz\{f_o, f_o\}} - \boldsymbol{T}_{x\{f\}} \boldsymbol{R}_{xz\{f, f_o\}} \right\|_{\mathrm{F}}^2 \\
\text{subject to} \quad & \sum_{k=1}^{K} \sigma_k^2 \left(\boldsymbol{T}_{\{f\}} \boldsymbol{R}_{xz\{f, f_o\}} \right) = \sum_{k=1}^{K} \sigma_k^2 \left(\boldsymbol{R}_{xz\{f, f_o\}} \right), \\
& \sum_{m=K+1}^{M} \sigma_m^2 \left(\boldsymbol{R}_{xz\{f, f_o\}} \right) = 0,
\end{aligned}$$

where $\sum_{k=1}^{K} \sigma_k^2 \left(\boldsymbol{A} \right)$ is the sum-of-squares K largest singular values of $\boldsymbol{A}$.

Research #2: New Solution for Estimating $\boldsymbol{T}_{x\{f\}}$ via $\boldsymbol{R}_{xz}$

Given a temporal frequency f, the solution matrices are defined as:

$$\boldsymbol{E}_{x\{f\}} = \boldsymbol{R}_{xz\{f,f_\circ\}}\boldsymbol{R}^{\mathsf{H}}_{xz\{f_\circ,f_\circ\}}.$$

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Proposed Theorem: Extension Theory of Orthogonal Procrustes

The one possible solution of the optimization problems are given as:

$$\boldsymbol{T}_{x\{f\}} = \boldsymbol{V}_{e_{\{f\}_s}}\boldsymbol{U}^{\dagger}_{e_{\{f\}_s}},$$

where $\boldsymbol{E}_{x\{f\}}$ is factorized via Generalized Singular-Value Decomposition;

$$\boldsymbol{E}_{x\{f\}} = \boldsymbol{U}_{e_{\{f\}_s}}\boldsymbol{\Sigma}_{e_{\{f\}_s}}\boldsymbol{V}^{\mathsf{H}}_{e_{\{f\}_s}} + \boldsymbol{U}_{e_{\{f\}_n}}\boldsymbol{\Sigma}_{e_{\{f\}_n}}\boldsymbol{V}^{\mathsf{H}}_{e_{\{f\}_n}}.$$

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Note that $\begin{bmatrix} \boldsymbol{U}_{e_{\{f\}_s}} & \boldsymbol{U}_{e_{\{f\}_n}} \end{bmatrix}$ is not unitary, $\boldsymbol{V}_{e_{\{f\}_s}}$ does not depend on f;

$$\boldsymbol{V}_{e_s} = \boldsymbol{V}_{e_{\{f_1\}_s}} = \boldsymbol{V}_{e_{\{f_2\}_s}} = \cdots = \boldsymbol{V}_{e_{\{f_P\}_s}}.$$

Research #2: New Solution for Estimating $\boldsymbol{T}_{x\{f\}}$ via $\boldsymbol{R}_{xz}$

Suppose we have a set of $\boldsymbol{E}_{x\{f_i\}} \in \mathbb{C}^{M \times M}$ and all of them have a full rank;

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\end{aligned}$$

Employing Generalized Singular-Value Decomposition, we have:

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\boldsymbol{E}_{x\{f_1\}} &= \boldsymbol{U}_{e_{\{f_1\}_s}}\boldsymbol{\Sigma}_{e_{\{f_1\}_s}}\boldsymbol{V}^{\mathrm{H}}_{e_{\{f_1\}_s}} + \boldsymbol{U}_{e_{\{f_1\}_n}}\boldsymbol{\Sigma}_{e_{\{f_1\}_n}}\boldsymbol{V}^{\mathrm{H}}_{e_{\{f_1\}_n}}, \\
\boldsymbol{E}_{x\{f_2\}} &= \boldsymbol{U}_{e_{\{f_2\}_s}}\boldsymbol{\Sigma}_{e_{\{f_2\}_s}}\boldsymbol{V}^{\mathrm{H}}_{e_{\{f_2\}_s}} + \boldsymbol{U}_{e_{\{f_2\}_n}}\boldsymbol{\Sigma}_{e_{\{f_2\}_n}}\boldsymbol{V}^{\mathrm{H}}_{e_{\{f_2\}_n}}, \\
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- **Question**: How to factorize it simultaneously (not separately)?

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\end{aligned}$$

- **Question**: How to factorize it simultaneously (not separately)?
- **Answer**: High-Order Generalized Singular-Value Decomposition

Research #2: New Solution for Estimating $\boldsymbol{T}_{x\{f\}}$ via $\boldsymbol{R}_{xz}$

Definition of High-Order Generalized Singular-Value Decomposition

$$\begin{bmatrix} \boldsymbol{E}_{x\{f_1\}} \\ \boldsymbol{E}_{x\{f_2\}} \\ \vdots \\ \boldsymbol{E}_{x\{f_P\}} \end{bmatrix} = \begin{bmatrix} \boldsymbol{U}_{e\{f_1\}_s} \boldsymbol{\Sigma}_{e\{f_1\}_s} \\ \boldsymbol{U}_{e\{f_2\}_s} \boldsymbol{\Sigma}_{e\{f_2\}_s} \\ \vdots \\ \boldsymbol{U}_{e\{f_P\}_s} \boldsymbol{\Sigma}_{e\{f_P\}_s} \end{bmatrix} \boldsymbol{V}_{e_s}^{\mathrm{H}} + \begin{bmatrix} \boldsymbol{U}_{e\{f_1\}_n} \boldsymbol{\Sigma}_{e\{f_1\}_n} \\ \boldsymbol{U}_{e\{f_2\}_n} \boldsymbol{\Sigma}_{e\{f_2\}_n} \\ \vdots \\ \boldsymbol{U}_{e\{f_P\}_n} \boldsymbol{\Sigma}_{e\{f_P\}_n} \end{bmatrix} \boldsymbol{V}_{e_n}^{\mathrm{H}}.$$

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Important Criteria: $\boldsymbol{V}_{e_s} = \boldsymbol{V}_{e_{\{f_1\}_s}} = \boldsymbol{V}_{e_{\{f_2\}_s}} = \cdots = \boldsymbol{V}_{e_{\{f_P\}_s}}$

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Research #2: New Solution for Estimating $\boldsymbol{T}_{x\{f\}}$ via $\boldsymbol{R}_{xz}$

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New Solution of $\boldsymbol{T}_{x\{f\}}$: $$\begin{bmatrix} \boldsymbol{T}_{x\{f_1\}} \\ \boldsymbol{T}_{x\{f_2\}} \\ \vdots \\ \boldsymbol{T}_{x\{f_P\}} \end{bmatrix} = \boldsymbol{V}_{e_s} \begin{bmatrix} \boldsymbol{U}^{\dagger}_{e\{f_1\}_s} \\ \boldsymbol{U}^{\dagger}_{e\{f_2\}_s} \\ \vdots \\ \boldsymbol{U}^{\dagger}_{e\{f_P\}_s} \end{bmatrix}$$

S.P. Ponnapalli *et al.*, "Higher-Order Generalized Singular Value Decomposition for Comparison of Global mRNA Expression from Multi-organisms," PLOS ONE, 2011.

Research #2: Performance Evaluation

- Performance under the reverberation environment (RT60)
- $\left(\theta_k^{\mathrm{DOA}}, \phi_k^{\mathrm{DOA}}\right)$ are placed at $(41.41^\circ, 60^\circ)$, $(60^\circ, 45^\circ)$, $(75.52^\circ, 30^\circ)$

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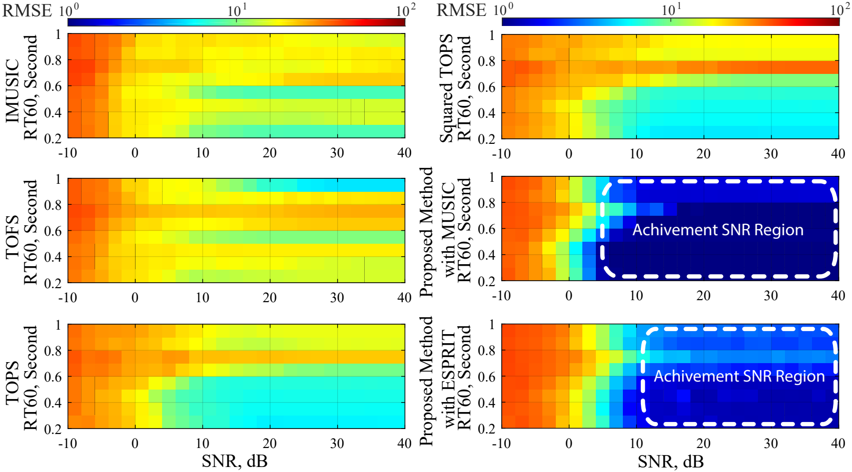
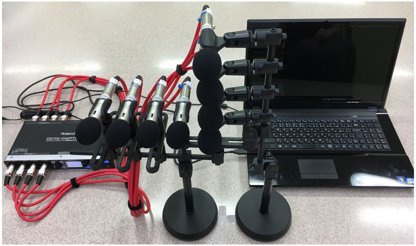


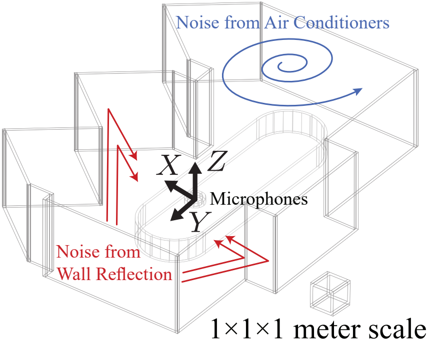
Research #2: Experimentation

- Experiment Setup :



- Number of Microphone : 8
- Capture time : 5 second
- Reverberation time : 0.3 second
- SNR value : 22.78 dB
- Focus only front direction

- Room Dimensions :



- KUT meeting room (A511)
- 2 - 3 People speak to the microphones simultaneity

Research #2: Experimental Result

- Performance under the real environment

Research #2: Experimental Result

- Performance under the real environment

Incident Sources			RMSE of DOAs (Degree)					
Number	Position	Angle (Degree)	IMUSIC	TOFS	TOPS	Squared TOPS	Proposed Method with MUSIC	Proposed Method with ESPRIT
1	ϕ_1	96	0.3050	**0.2050**	1.0950	1.3350	0.7750	0.7074
	θ_1	86	**0.5400**	1.2600	1.2750	2.0150	0.5700	0.6915
		Average	**0.4225**	0.7325	1.1850	1.6750	0.6725	0.6995
2	ϕ_1	65	**1.1857**	1.7286	20.0143	28.5857	1.5000	2.0284
	θ_1	150	9.6000	6.6857	26.3571	39.7857	8.8143	**8.6800**
	ϕ_2	55	**1.0714**	1.6857	22.2571	19.4000	2.9714	3.8695
	θ_2	100	8.3714	8.3857	5.0143	6.7857	6.6714	**3.1630**
		Average	5.0571	4.6214	18.4107	23.6393	4.9893	**4.4353**
3	ϕ_1	58	**2.1400**	2.3900	46.5500	52.8100	3.6600	4.0334
	θ_1	55	55.0000	55.0000	55.0000	55.0000	9.4300	**4.1057**
	ϕ_2	100	**1.8400**	2.0000	41.5700	62.4000	1.8700	2.4554
	θ_2	95	95.0000	83.4200	52.4500	71.4800	9.7700	**5.8638**
	ϕ_3	130	10.9300	11.8900	28.8300	32.2800	8.2500	**6.9071**
	θ_3	120	26.9800	25.8400	16.1200	18.0100	**5.9400**	7.3165
		Average	31.9817	30.0900	40.0867	48.6633	6.4867	**5.1137**

Research #2: References

[IMUSIC] G. Su *et al.*, "The signal subspace approach for multiple wide-band emitter location," 1983.

[TOPS] Y. S. Yoon *et al.*, "Tops: new doa estimator for wideband signals," 2006.

[TOFS] H. Yu *et al.*, "A new method for wideband doa estimation," 2007.

[Squared-TOPS] K. Okane *et al.*, "Resolution improvement of wideband direction-of-arrival estimation "squared-tops"," 2010.

[MUSIC] R. Schmidt, "Multiple emitter location and signal parameter estimation ," 1986.

[ESPRIT] R. Roy *et al.*, " ESPRIT-estimation of signal parameters via rotational invariance techniques," 1989.

Presentation Outline

1. Introduction: Preliminary Assessment, Objective, and New Approaches
2. Research #1: Acoustic DOA Estimation by using Theory of Orthogonal Procrustes Analysis
3. Research #2: Extension Theory of Orthogonal Procrustes Analysis for Acoustic DOA Estimation
4. Research #3: Acoustic DOA and Variance Estimation via Complex-Valued Tensor Factorization
5. Summary: Conclusions

Research #3: Problem with Previously Version

- In research #1, accuracy performance of acoustic DOA estimation is improved, but information of frequency bins are compressed and lost
- In research #2, the accuracy performance is further improved, but we didn't address how to obtain information of frequency bins

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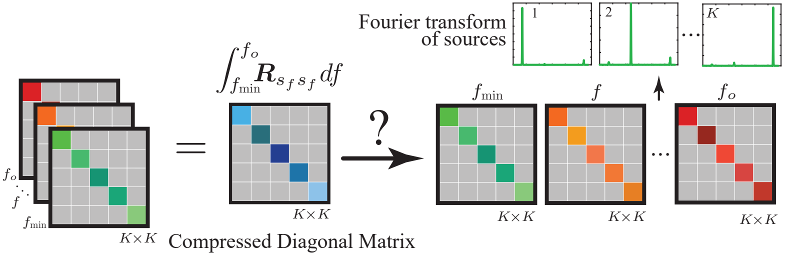

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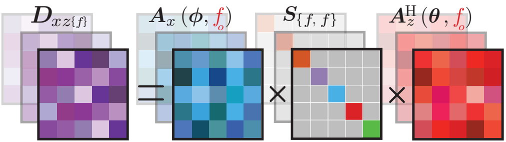
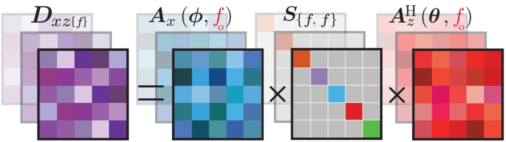
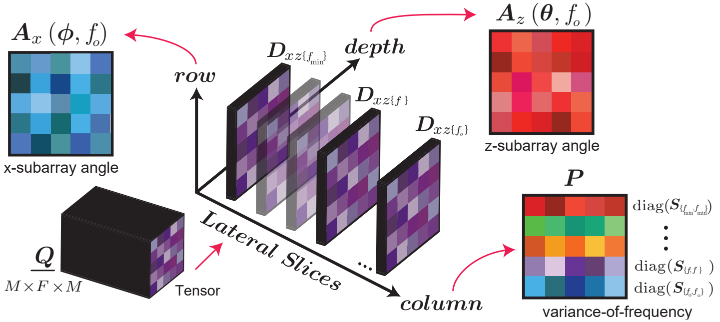




- Given an 3rd-order tensor $\underline{\boldsymbol{Q}} \in \mathbb{C}^{M \times F \times M}$ and the inner index K
- $\boldsymbol{D}_{xz\{f\}}$ are rearranged by lateral slices of $\underline{\boldsymbol{Q}}$



Research #3: New Sample Cross-correlation

Tensor Representation

$$\underline{\boldsymbol{Q}} = \left[\left[\boldsymbol{A}_x\left(\phi, f_\mathrm{o}\right), \boldsymbol{P}, \bar{\boldsymbol{A}}_z\left(\theta, f_\mathrm{o}\right)\right]\right],$$

$$\underline{\boldsymbol{Q}}_{:,f,:} = \boldsymbol{D}_{xz\{f\}}, \text{(lateral slice represent.)}$$

$$\boldsymbol{D}_{xz\{f\}} = \boldsymbol{T}_{x\{f\}} \boldsymbol{R}_{xz\{f,f\}} \boldsymbol{T}^{\mathrm{H}}_{z\{f\}}.$$

- $\boldsymbol{R}_{xz\{f,f\}} \in \mathbb{C}^{M\times M}$ is the sample cross-correlation matrix
- $\boldsymbol{T}_{x\{f\}}, \boldsymbol{T}_{z\{f\}} \in \mathbb{C}^{M\times M}$ are the transformation matrices
- $\boldsymbol{A}_x\left(\boldsymbol{\phi}, f\right), \boldsymbol{A}_z\left(\boldsymbol{\theta}, f\right) \in \mathbb{C}^{M\times K}$ is the array manifold matrices
- $\bar{\boldsymbol{A}}_z\left(\theta, f_\mathrm{o}\right) \in \mathbb{C}^{M\times K}$ is complex conjugate of the elements of $\boldsymbol{A}_z\left(\theta, f_\mathrm{o}\right)$
- $\boldsymbol{P} \in \mathbb{R}^{F\times K}_{\geq 0}$ is the sample variance matrix for all frequency

Research #3: DOA Estimation via Tensor Factorization

- To isolate $\boldsymbol{A}_x, \boldsymbol{P}, \boldsymbol{A}_z$ from $\underline{\boldsymbol{Q}}$, tensor factorization is employed
- Employing Complex-valued Parallel Factor Analysis model; [1]

$$\boldsymbol{P} = \begin{pmatrix} \sigma^2_{s_1\{f_{\min}\}} & \sigma^2_{s_2\{f_{\min}\}} & \cdots & \sigma^2_{s_K\{f_{\min}\}} \\ \vdots & \vdots & \ddots & \vdots \\ \sigma^2_{s_1\{f\}} & \sigma^2_{s_2\{f\}} & \cdots & \sigma^2_{s_K\{f\}} \\ \vdots & \vdots & \ddots & \vdots \\ \sigma^2_{s_1\{f_\mathrm{o}\}} & \sigma^2_{s_2\{f_\mathrm{o}\}} & \cdots & \sigma^2_{s_K\{f_\mathrm{o}\}} \end{pmatrix}$$

- $\sigma^2_{s_k\{f\}}$ is a variance of the signal source $s_k(\boldsymbol{t}, f)$ or **singular values**
- Estimate DOA angles [2] : $\boldsymbol{U} \equiv \boldsymbol{A}_x(\phi, f_\mathrm{o}),\ \boldsymbol{V} \equiv \boldsymbol{A}_z(\theta, f_\mathrm{o})$

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[1] N.D.Sidiropoulos *et al.*, "Blind PARAFAC Receivers for DS-CDMA System," 2000.

[2] B.Suksiri *et al.*, "A Highly Efficient Wideband Two-Dimensional Direction Estimation Method with L-Shaped Microphone Array," IEICE-EA, 2019.

Research #3: Variance Estimation Performance

The three sources were the following piano notes; (a, d) G5 - 783.99 Hz, (b, e) C5 or Tenor C (523.25 Hz), (c, f) A4 or A440 (440 Hz).

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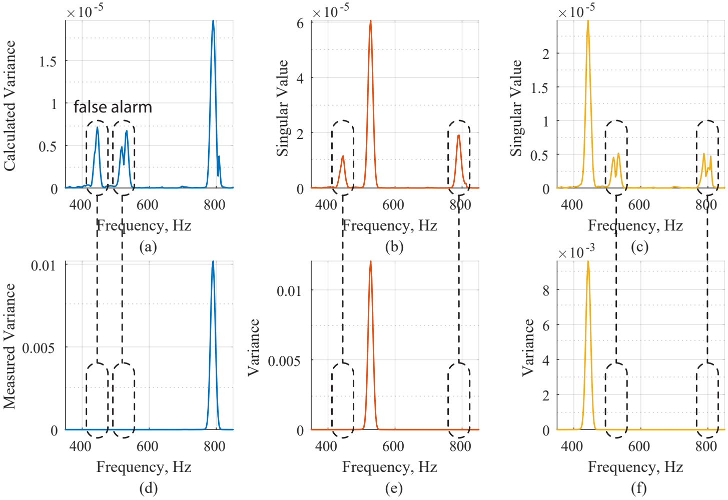

Research #3: Angle Estimation Performance

$\left(\theta_k^{\mathrm{DOA}}, \phi_k^{\mathrm{DOA}}\right)$ are placed at $(41.41^\circ, 60^\circ)$, $(60^\circ, 45^\circ)$, and $(75.53^\circ, 30^\circ)$

Research #3: Angle Estimation Performance

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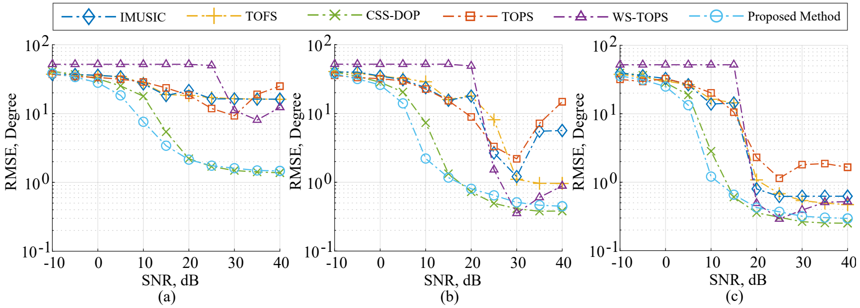

Number of microphone each subarray on (a) = 6, (b) = 8, and (c) = 10

Research #3: Angle Estimation Performance

- [IMUSIC] G.Su *et al.*, "The signal subspace approach for multiple wide-band emitter location," 1983.
- [TOPS] Y.S.Yoon *et al.*, "Tops: new doa estimator for wideband signals," 2006.
- [TOFS] H.Yu *et al.*, "A new method for wideband doa estimation," 2007.
- [WS-TOPS] H.Hirotaka *et al.*, "Doa estimation for wideband signals based on weighted squared tops," 2016.
- [CSS-DOP] B.Suksiri *et al.*, "A Highly Efficient Wideband Two-Dimensional Direction Estimation Method with L-Shaped Microphone Array," IEICE-EA, 2019.

Presentation Outline

1. Introduction: Preliminary Assessment, Objective, and New Approaches
2. Research #1: Acoustic DOA Estimation by using Theory of Orthogonal Procrustes Analysis
3. Research #2: Extension Theory of Orthogonal Procrustes Analysis for Acoustic DOA Estimation
4. Research #3: Acoustic DOA and Variance Estimation via Complex-Valued Tensor Factorization
5. Summary: Conclusions

Summary: Conclusions, Contribution

Conclusions:

- An extension of techniques, new framework and suitable theory for estimating acoustic DOAs are presented.

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Conclusions:

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Contribution:

- This work bridge a research gap of acoustic source compatibility on the recent narrowband and wideband subspace methods to estimate DOA of the acoustic sources directly and effectively.

Summary: Publications

- **Authors:** Bandhit Suksiri, Masahiro Fukumoto
- **Journal papers:**
  #1. **Submitted to:** J-STAGE Journal of Signal Processing
  Tittle: Multiple Frequency and Source Angle Estimation by Gaussian Mixture Model with Modified Microphone Array Data Model
  Status: published on July 20, 2017
  #2. **Submitted to:** IEICE Transactions on Fundamentals of Electronics, Communications and Computer Sciences (IEICE-EA)
  Tittle: A Highly Efficient Wideband Two-Dimensional Direction Estimation Method with L-Shaped Microphone Array
  Status: accepted on July 31, 2019, publication in November 2019
  Rank: Q4 (JCR 2018)
  #3. **Submitted to:** Sensors
  Tittle: An Efficient Framework for Estimating Direction of Multiple Sound Sources using Higher-Order Generalized Singular Value Decomposition
  Status: published on July 5, 2019
  Rank: Q1 (JCR 2018)

Summary: Publications

- **Peer-reviewed international conference:**
  - #1. **Conference:** 14th RISP International Workshop on Nonlinear Circuits, Communications and Signal Processing (RISP NCSP'17)
    Tittle: Multiple Frequency and Source Angle Estimation by Gaussian Mixture Model with Modified Microphone Array Data Model
    Award: Student Paper Award
  - #2. **Conference:** 9th Asia-Pacific Signal and Information Processing Association Annual Summit and Conference (APSIPA ASC 2017)
    Tittle: Enhanced Array Manifold Matrices for L-Shaped Microphone Array-based 2-D DOA Estimation
  - #3. **Conference:** 50th IEEE International Symposium on Circuits and Systems (ISCAS 2018)
    Tittle: A Computationally Efficient Wideband Direction-of-Arrival Estimation Method for L-Shaped Microphone Arrays
    Award: IEEE CAS Student Travel Grant Award
  - #4. **Conference:** 16th International Conference on Electrical Engineering/Electronics, Computer, Telecommunications and Information Technology (ECTI-CON 2019)
    Tittle: Wideband Direction-of-Arrival Estimation with Cross-Sample

Summary: Publications

- **Domestic conference:**
  - #1. **Conference:** 31st Signal Processing Symposium (31st SIP SYMPOSIUM)
    Tittle: Wavelet Analysis for Multiple Frequency and Signal Classification in Linear Phased Array Model (presenting in English)
  - #2. **Conference:** 32nd Signal Processing Symposium (32nd SIP SYMPOSIUM)
    Tittle: A Novel L-Shaped Microphone Array-based Wideband Direction of Arrival Estimation Method using the Special Cross-correlation Matrix (presenting in English)
  - #3. **Conference:** 33rd Signal Processing Symposium (33rd SIP SYMPOSIUM)
    Tittle: Complex-valued Tensor Factorization on Wideband Two-dimensional Direction Estimation Method with L-Shaped Microphone Array (presenting in Japanese)