Spatial Sound Mapping via Constrained Spectral Conditioning and CLEAN-SC

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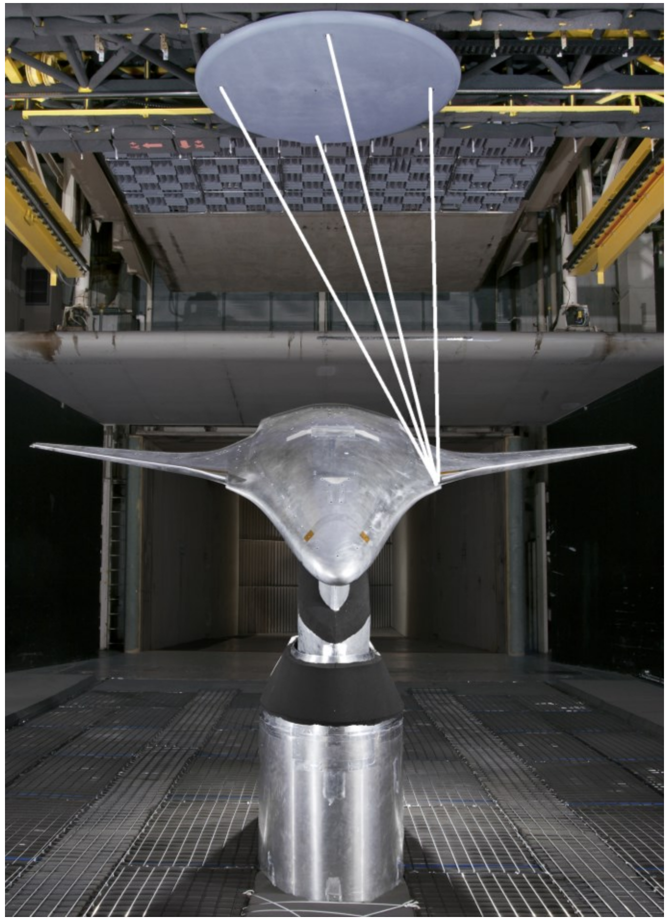
Problem Statement

- Spatially map sound with qualitative/quantitative accuracy
- Microphone arrays allow for spatial separation of distinct sources
- Many existing processing methods



Downstream view of Hybrid Wing Body model inverted on test stand with phased microphone array overhead

Existing Spatial Sound Mapping Methods in Aeroacoustics

- Cross-spectral
  - Beamforming
  - CLEAN-PSF *[Högbom 1974]*
  - Spectral Estimation Method *[Blacodon & Élias 2003]*
  - DAMAS and DAMAS-C *[Brooks & Humphreys 2004, 2006]*
  - CLEAN-SC *[Sijtsma 2007]*
  - Functional Beamforming *[Dougherty 2014]*
- Eigenspace
  - Generalized Inverse *[Suzuki 2008]*
  - Orthogonal Beamforming *[Sarradj 2010]*
- Wavespace
  - Wavespace Deconvolution *[Bahr & Cattafesta 2012]*

Research Objectives

- ***Use:***
  - Single-channel filtering based on user-defined spatial constraints

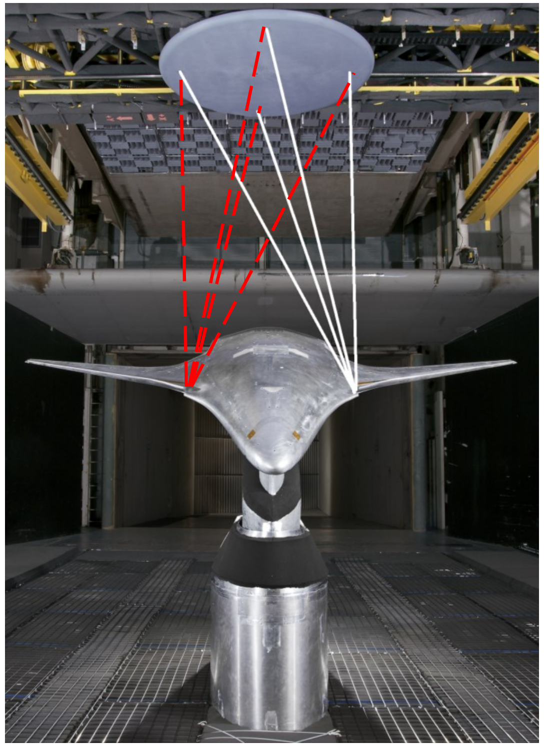
- ***As:***
  - Building-block for existing spatial mapping techniques

- ***For:***
  - Qualitative/quantitative improvement in accuracy

Microphone Array Filtering

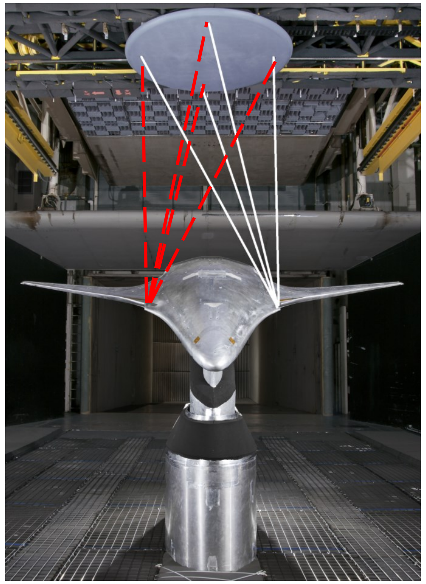
- Goal: Filter channel data for more accurate spatial sound estimation

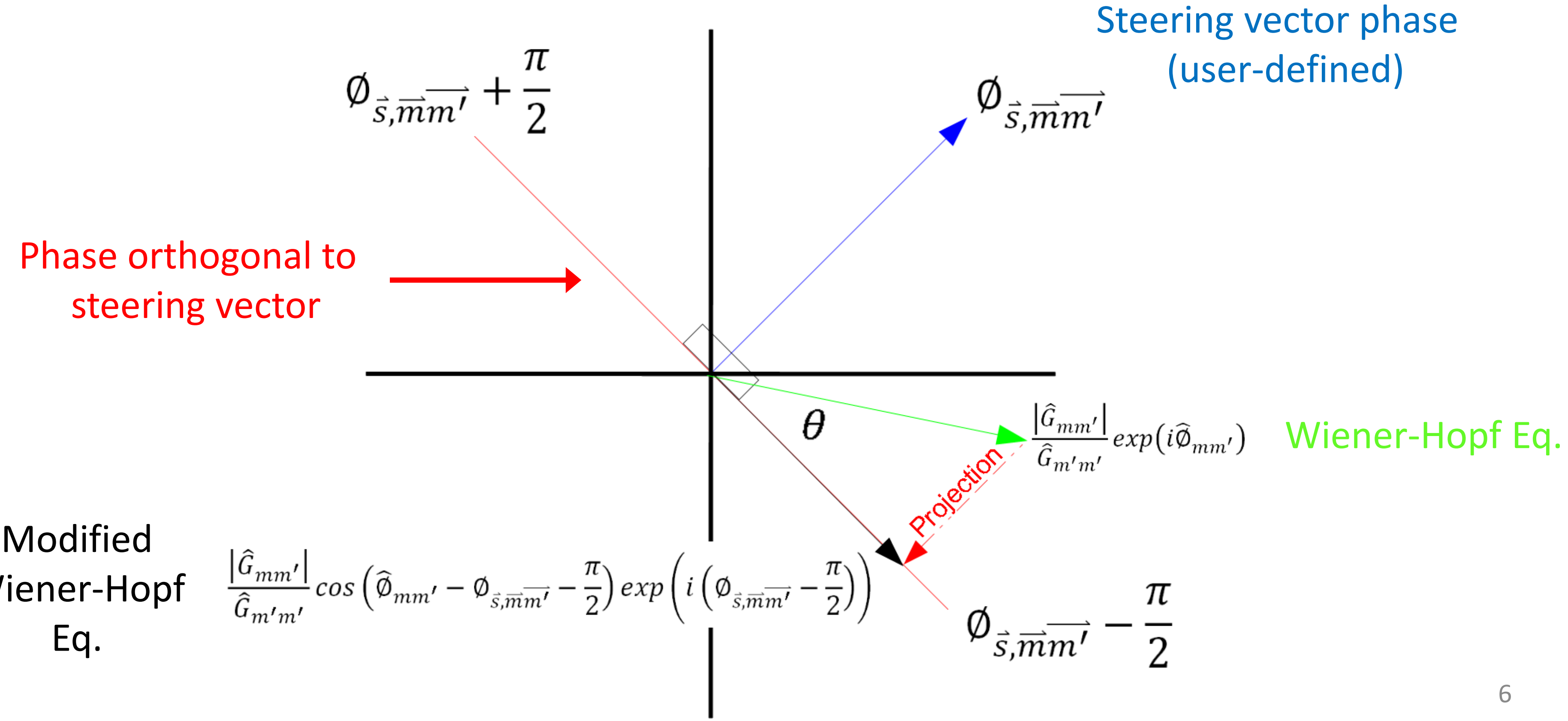
Filter dashed-red to
better estimate solid-white



Modified Wiener-Hopf Eq. for Spatial Filtering

- Combine: Optimal, least-squares filtering of Wiener-Hopf Eq. + Spatial filtering
- Only constraint = User-defined phase
- Modified weight vector → Filters + Prevents targeted signal cancellation





Constrained Spectral Conditioning (CSC)

- Conditioned Spectral Analysis[1] with modified Wiener-Hopf Eq. (WB) becomes CSC[2]
- Optimal, spatially-constrained, least-squares filtering for Fourier Transforms of microphone outputs

Wiener-Hopf Eq.

$$W = \frac{|\hat{G}_{mm'}|}{\hat{G}_{m'm'}} exp(i\hat{\emptyset}_{mm'})$$

$$\downarrow$$

Modified Wiener-Hopf Eq. via Orthogonal Projection

$$WB = \frac{|\hat{G}_{mm'}|}{\hat{G}_{m'm'}} cos\left(\hat{\emptyset}_{mm'} - \emptyset_{\vec{s},\overrightarrow{mm'}} - \frac{\pi}{2}\right) exp\left(i\left(\emptyset_{\vec{s},\overrightarrow{mm'}} - \frac{\pi}{2}\right)\right)$$

$$\downarrow$$

Constrained Spectral Conditioning

$$CH_{m,m'removed} = CH_m - WB[CH_{m'}]$$

[1]Bendat & Piersol 1986, [2]Spalt 2014

Basic Spatial Sound Mapping

Frequency-Domain Beamforming (FDBF) (a.k.a. Delay-and-Sum (DAS))

Steering Vector

$$e_{\vec{s},\vec{m}} = A_{\vec{s},\vec{m}} exp\left(i\emptyset_{\vec{s},\vec{m}}\right)$$

Steering Vector Matrix

$$e_{\vec{s}} = [e_{\vec{s},1} \quad e_{\vec{s},2} \quad \cdots \quad e_{\vec{s},M}]$$

Cross-Spectral Matrix (CSM)

$$\hat{G} = \begin{bmatrix} \hat{G}_{11} & \hat{G}_{12} & \cdots & \hat{G}_{1M} \\ \hat{G}_{21} & \ddots & & \vdots \\ \vdots & & \ddots & \vdots \\ \hat{G}_{M1} & \cdots & \cdots & \hat{G}_{MM} \end{bmatrix}$$

FDBF

$$Y_{\vec{s}} = \left(\frac{1}{M^2}\right) e_{\vec{s}}^T \hat{G} e_{\vec{s}}$$

CSM formed from CSC outputs = "CSC-CSM"

FDBF via CSC

$$e_{\vec{s},\vec{m}} = A_{\vec{s},\vec{m}} exp\left(i\emptyset_{\vec{s},\vec{m}}\right)$$

$$e_{\vec{s}} = [e_{\vec{s},1} \quad e_{\vec{s},2} \quad \cdots \quad e_{\vec{s},M}]$$

$$\hat{G}_{\vec{s},CSC} = \begin{bmatrix} \hat{G}_{\vec{s},11} & \hat{G}_{\vec{s},12} & \cdots & \hat{G}_{\vec{s},1M} \\ \hat{G}_{\vec{s},21} & \ddots & & \vdots \\ \vdots & & \ddots & \vdots \\ \hat{G}_{\vec{s},M1} & \cdots & \cdots & \hat{G}_{\vec{s},MM} \end{bmatrix}$$

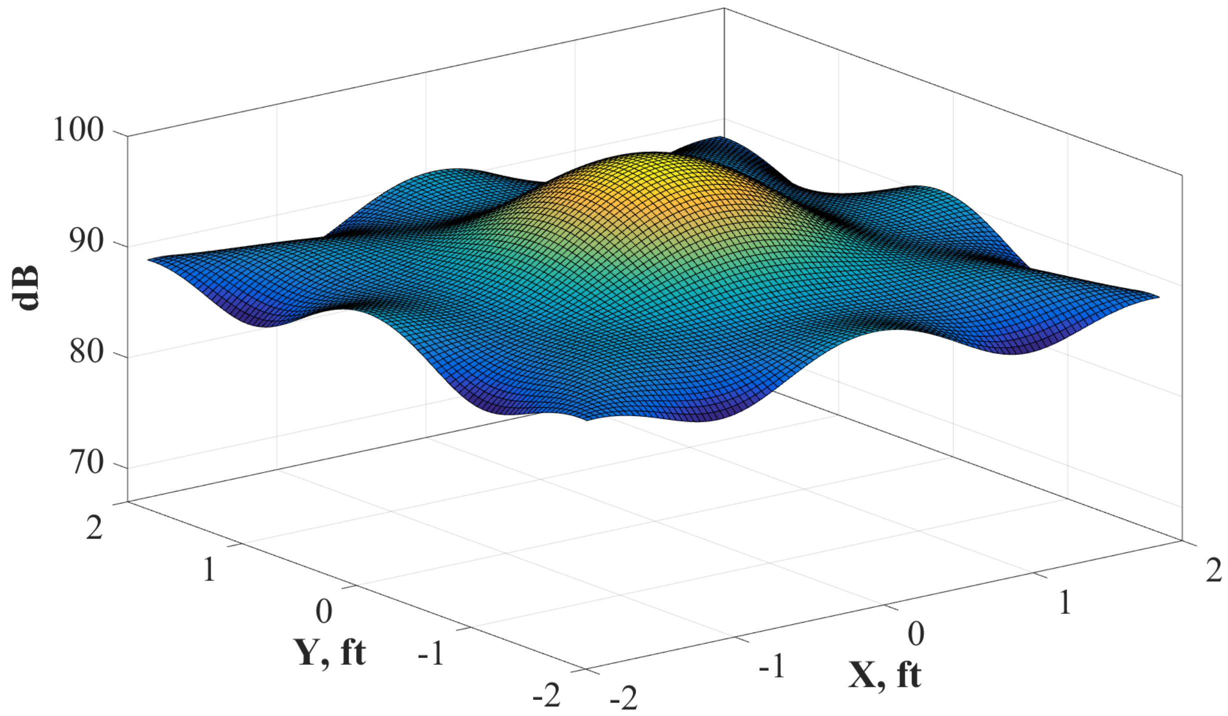
FDBF via CSC

$$Y_{\vec{s},CSC} = \left(\frac{1}{M^2}\right) e_{\vec{s}}^T \hat{G}_{\vec{s},CSC} e_{\vec{s}}$$

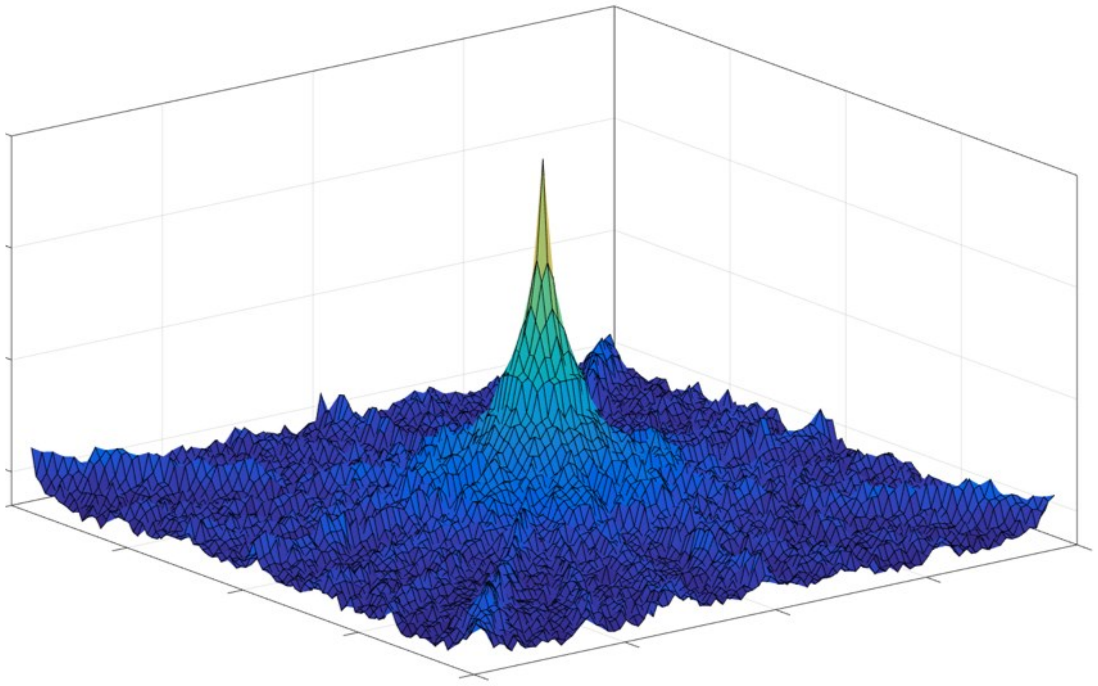
FDBF Beamwidth and Sidelobes: Simulated Point Source

- Point source “measured” with SADA[1]: 60” from array face, *f* = 10 kHz, SNR = 20 dB

FDBF via Initial CSM



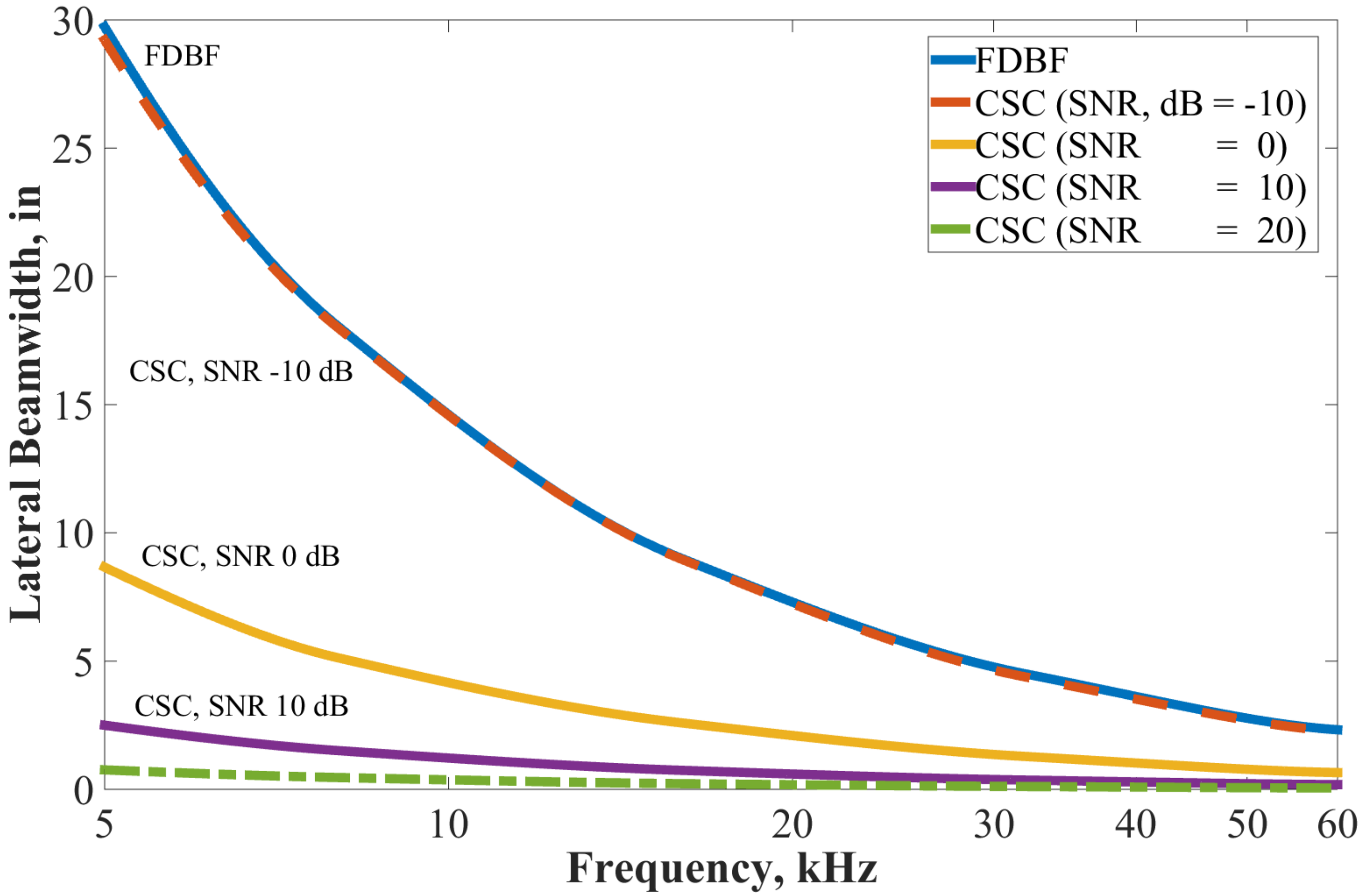
FDBF via CSC-CSM



[1]*Humphreys et al. 1998*

FDBF Beamwidth & Highest Sidelobe Level vs. Frequency

- CSC performance dependent on SNR & frequency



SNR, dB	Highest Sidelobe of FDBF via CSC-CSM relative to highest sidelobe of FDBF via initial CSM, dB
-10	0
0	-5.5
10	-12.3
20	-19.6

CSC Observations

- Constrained Spectral Conditioning (CSC)
  - Single-channel processing → ***Building-block for existing algorithms*** as it processes the Fourier Transforms of microphone outputs
  - Uses only relative phase differences as constraints

- CSC success dependent on:
  - Frequency
  - Source field
  - Solid angle
  - Microphone layout
  - Signal-to-Noise Ratio (SNR)

CSC Observations, cont.

- CSC output datasets (“CSC-CSMs”) are estimates

- FDBF using CSC-CSMs
  - Non-integrateable (due to inaccuracies)
  - Non-linear → Cannot be deconvolved “easily”

➢ ***Modified approach needed for accurate spatial sound mapping***

Advanced Spatial Sound Mapping via CSM Decomposition

- CLEAN-PSF[1]

Iterate

$$Y^i_{\vec{s}} = \left(\frac{1}{M^2}\right) e^T_{\vec{s}} \hat{G}^i e_{\vec{s}}, \quad \vec{s} \in \vec{S}$$

FDBF to locate max location on map

PSF

$$\hat{G}^{i+1} = \hat{G}^i - \varphi Y^i_{\vec{s}_{max}} \left[e_{\vec{s}_{max}} e^T_{\vec{s}_{max}} \right]$$

Subtract CSM estimate

$$Stop\ if: \quad \sum \left|\hat{G}^i\right| \geq \sum \left|\hat{G}^{i-1}\right|$$

Iteration stop criterion

$$Y_{CLEAN-PSF} = \varphi \sum_{i=1}^{I} Y^i_{\vec{s}_{max}}$$

Output source map

- Pros
  - Takes advantage of "uncovered" information
- Cons
  - No sidelobe discrimination
  - Relies on the PSF for source propagation model

[1]*Högbom 1974*

Advanced Spatial Sound Mapping via CSM Decomposition, cont.

- CLEAN-CSC[1]

Iterate

$$Y_{\vec{s}}^{i} = \left(\frac{1}{M^2}\right) e_{\vec{s}}^{T} \hat{G}^{i} e_{\vec{s}}, \quad \vec{s} \in \vec{S}$$

FDBF to locate max location on map

CSC-CSM

$$\hat{G}^{i+1} = \hat{G}^{i} - \varphi Y_{\vec{s}_{max},CSC} \left[\hat{G}_{\vec{s}_{max},CSC}\right]$$

Subtract CSM estimate

$$\textit{Stop if}: \quad \sum \left|\hat{G}^{i}\right| \geq \sum \left|\hat{G}^{i-1}\right|$$

Iteration stop criterion

$$Y_{CLEAN-CSC} = \varphi \sum_{i=1}^{I} Y_{\vec{s}_{max},CSC}$$

Output source map

- Pros
  - Higher location/level accuracy than FDBF
  - Sidelobe discrimination
  - Does not use PSF magnitudes
- Cons
  - CSC-CSMs have inaccuracies
  - PSF phase still used
  - Cannot take advantage of “uncovered” information

[1] *Spalt 2014*

Advanced Spatial Sound Mapping via CSM Decomposition, cont.

- CLEAN-SC[1]

Iterate

$$Y_{\vec{s}}^{i} = \left(\frac{1}{M^2}\right) e_{\vec{s}}^{T} \hat{G}^{i} e_{\vec{s}}, \quad \vec{s} \in \vec{S}$$

FDBF to locate max location on map

$$h_{\vec{s}_{max}}^{i} = \left(\frac{1}{\sqrt{1 + w_{\vec{s}_{max}}^{T} H^{i} w_{\vec{s}_{max}}}}\right) \frac{\hat{G}^{i} w_{\vec{s}_{max}}}{Y_{\vec{s}_{max}}^{i}}$$

Form CSM estimate

CLEAN-SC-CSM

$$\hat{G}^{i+1} = \hat{G}^{i} - \varphi Y_{\vec{s}_{max}}^{i} \boxed{\left[h_{\vec{s}_{max}}^{i} \, h_{\vec{s}_{max}}^{i\,T}\right]}$$

Subtract CSM estimate

$$Stop\ if: \quad \sum \left|\hat{G}^{i}\right| \geq \sum \left|\hat{G}^{i-1}\right|$$

Iteration stop criterion

$$Y_{CLEAN-SC} = \varphi \sum_{i=1}^{I} Y_{\vec{s}_{max}}^{i}$$

Output source map

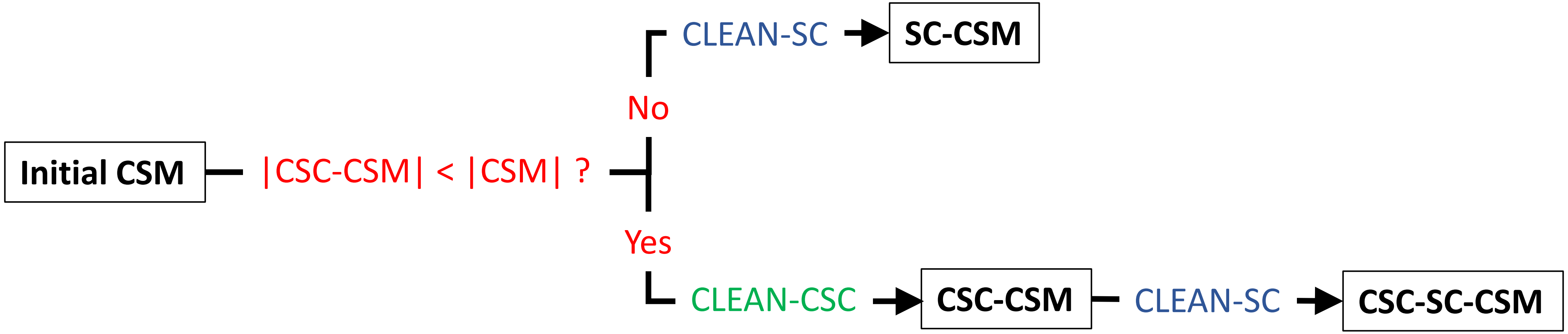
- Pros
  - Adaptively defines CSM estimate magnitudes/phases
  - Takes advantage of "uncovered" information

- Cons
  - No sidelobe discrimination
  - Multiple/distributed sources bias CSM estimate
  - Stronger sources bias weaker sources
  - Inaccurate for coherent sources

[1]Sijtsma 2007

CLEAN-CSC + CLEAN-SC → CLEAN-CSC-SC[1]

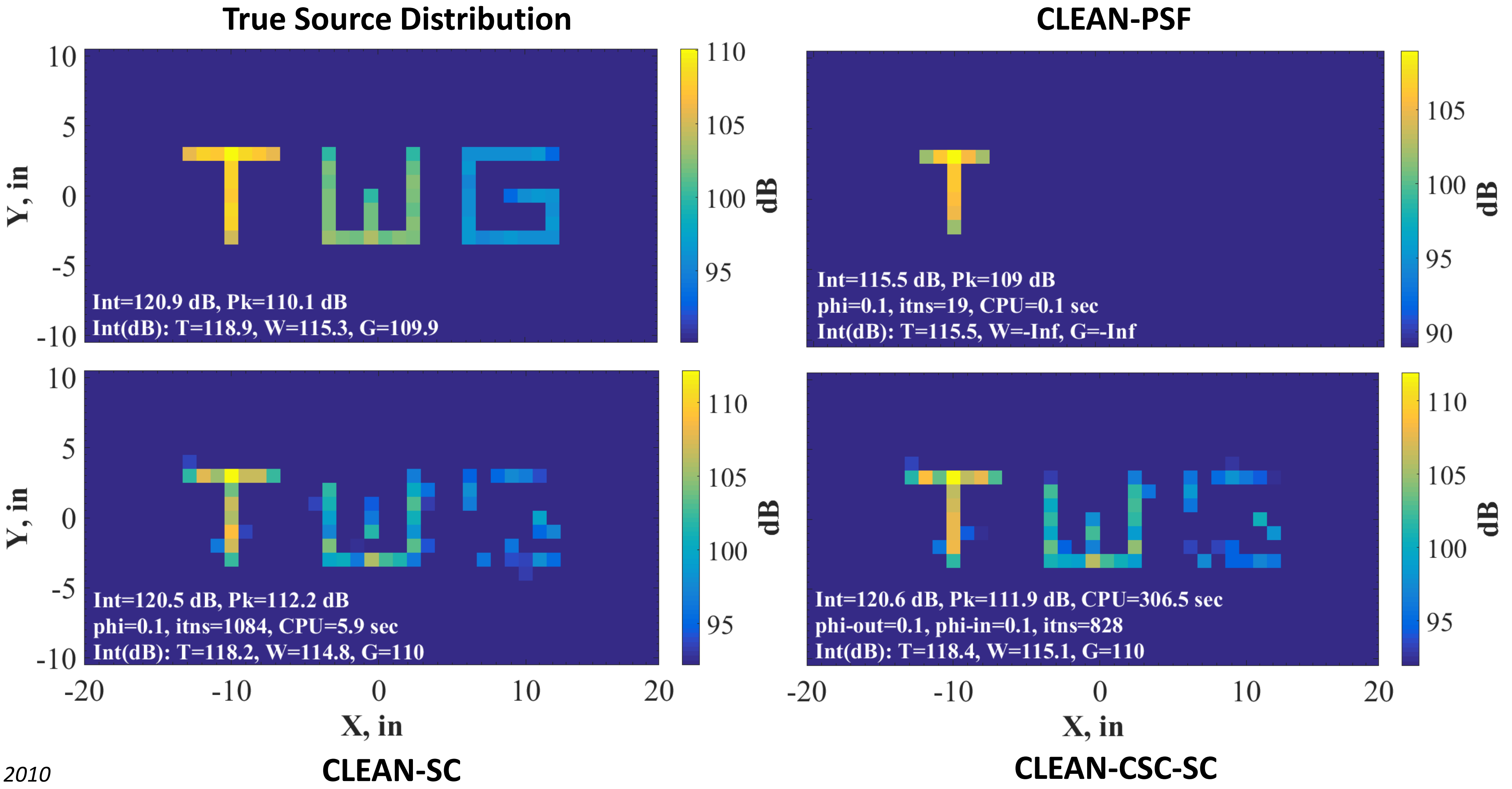
- CSC → FDBF and CSM at max locations
- CLEAN-SC → Further decompose CSC-CSM → CSC-SC-CSM
  - Improves CSC-CSM magnitude estimates
  - Corrects deviations in initial phase definitions
- CLEAN-SC only used once original CSM is sufficiently decomposed
  - Improves dynamic range



[1]*Spalt et al. 2015*

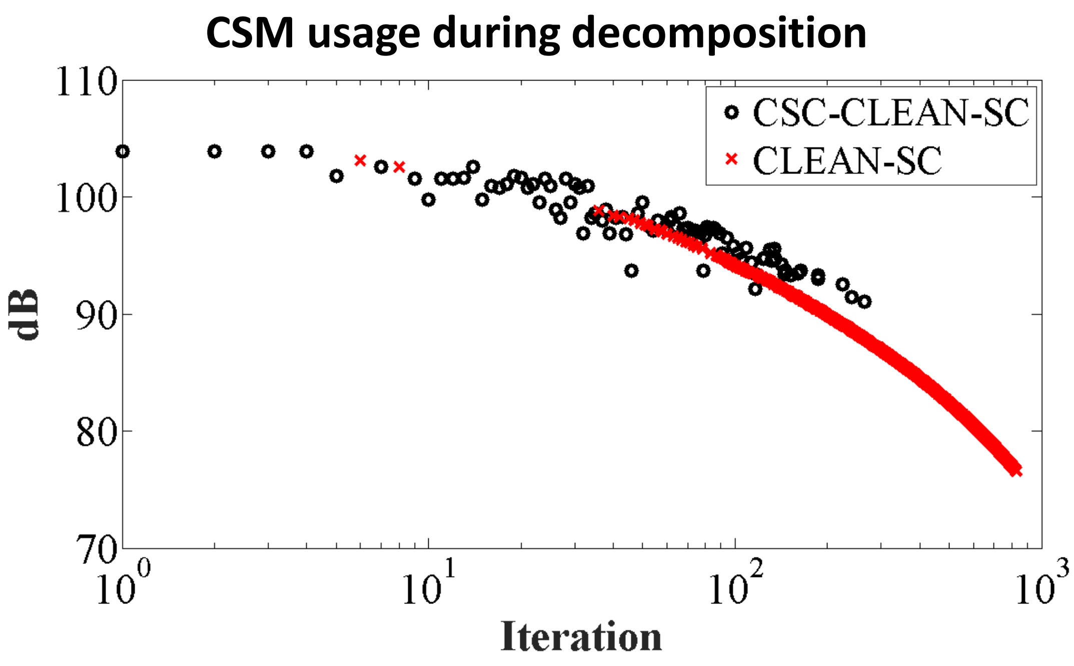
Simulation: Modified PSF, Incoherent Sources

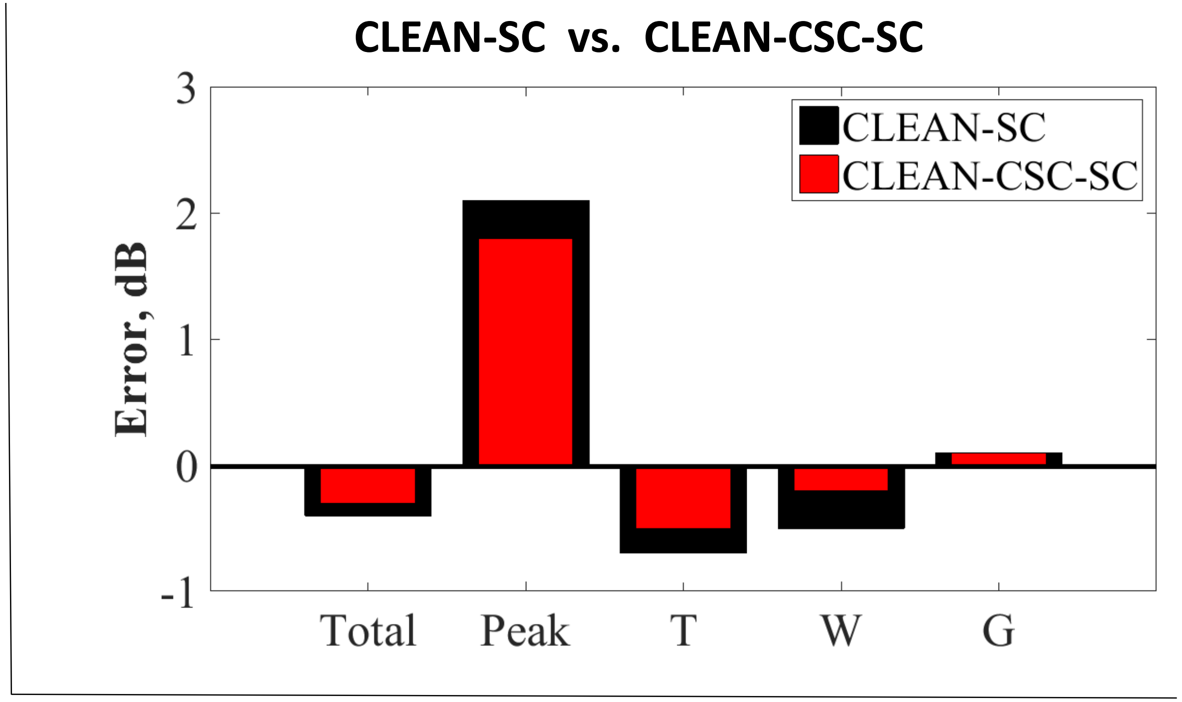
- <u>467 point sources "measured" with JEDA[1]:</u> 72" from array face, f = 15 kHz, SNR = 20 dB

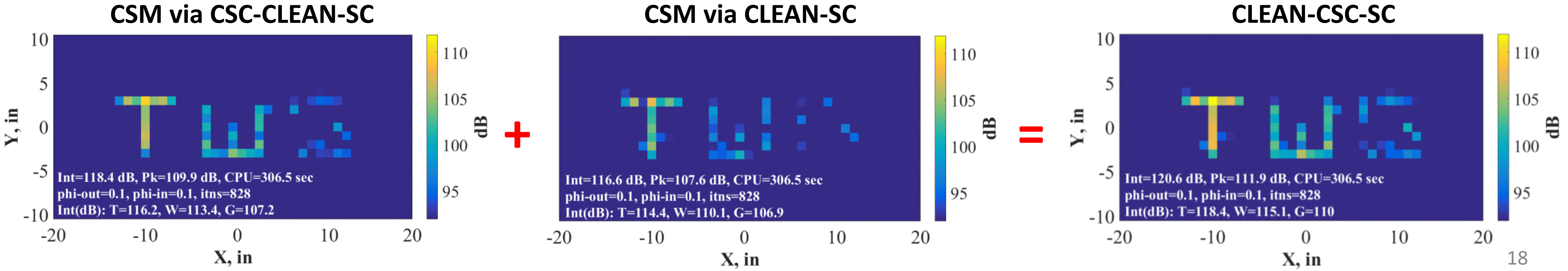


[1]*Brooks et al. 2010*

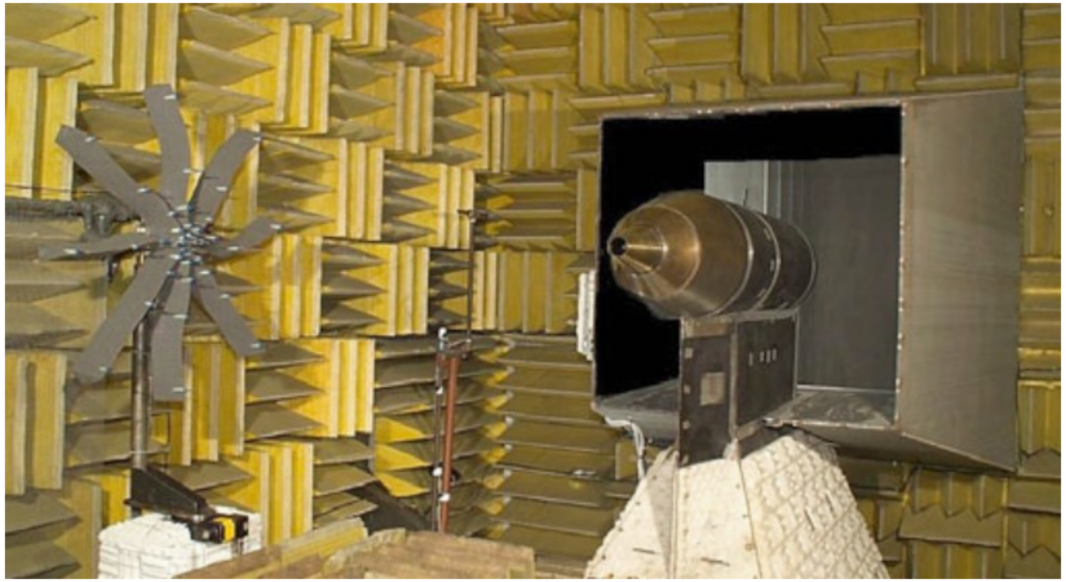
Simulation: Modified PSF, Incoherent Sources, cont.







Preliminary Jet Noise Results



JEDA (left) positioned at 90° with respect to the jet exit plane in the JNL.

- Single-stream, convergent nozzle
- Exit diameter 2.67”
- Supersonic, cold jet at Mach 1.48
- Wind tunnel co-flow at Mach 0.1
- Array (“JEDA”) 6 ft from jet centerline

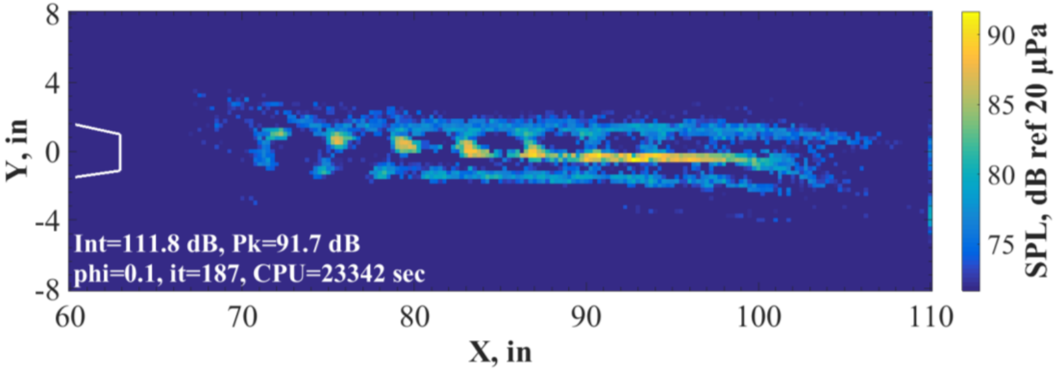
Preliminary Jet Noise Results, cont.

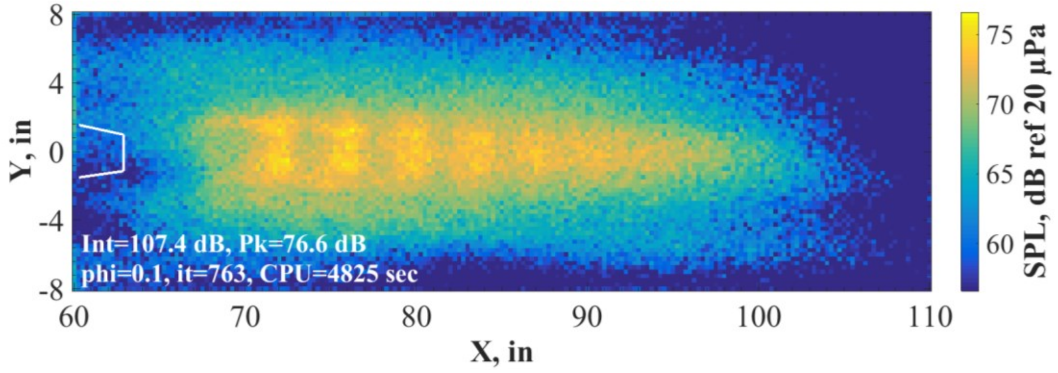
- **No CSM Diagonal Removal, No CSM Weighting**

8 kHz 1/3 oct, Mean Array Single Mic level = 113.1 dB

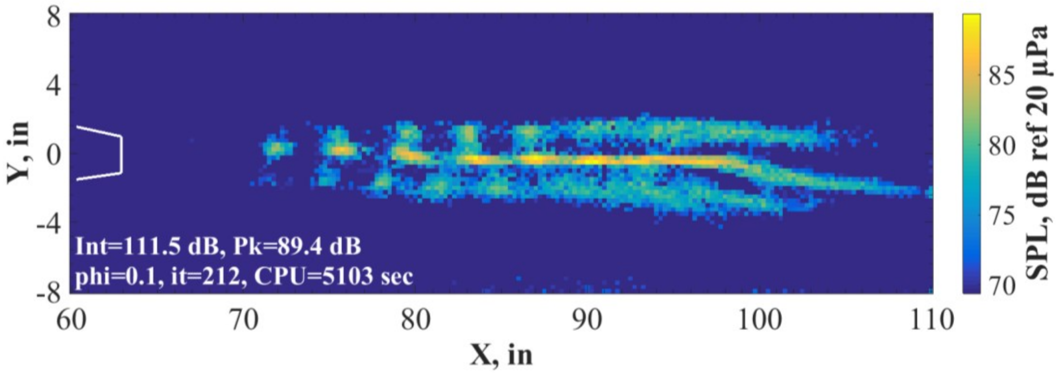
32 kHz 1/3 oct, Mean Array Single Mic level = 108.3 dB

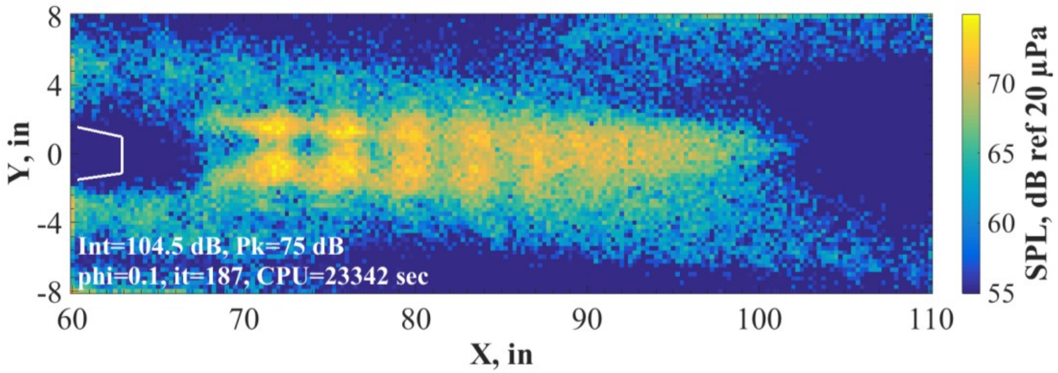
CLEAN-SC





CLEAN-CSC-SC





CSC Conclusions

- Building block for existing algorithms
- Improves result accuracy under incoherent source conditions
- Not “plug-and-play” for advanced spatial mapping algorithms

CLEAN-CSC-SC Conclusions

- More qualitatively/quantitatively accurate than CLEAN-SC for incoherent sources
- More analysis needed when source coherence exists

Acknowledgements

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  - NASA Project # NNL08AA00B
  - NASA Pathways Program

- This work would not have been possible without the support of:
  - Dr. Chris Fuller
  - Dr. Tom Brooks
  - Dr. Charlotte Whitfield
  - LaRC Aeroacoustics Branch
  - National Institute of Aerospace

Backup Slides

CLEAN-CSC-SC[1]

- Spatial sound mapping via decomposition of the initial CSM using CSC[2] and CLEAN-SC[3]

$$Y_{\vec{s}}^{i} = \left(\frac{1}{M^2}\right) e_{\vec{s}}^{T} \widehat{G}^{i} e_{\vec{s}}, \quad \vec{s} \in \vec{S}$$

1. Beamform to locate max grid location

$$Y_{\vec{s}_{max},CSC} = \left(\frac{1}{M^2}\right) e_{\vec{s}_{max}}^{T} \widehat{G}_{\vec{s}_{max},CSC} e_{\vec{s}_{max}}$$

2. Calculate CSC beamform estimate at max location using a CSC-CSM

$$h_{\vec{s}_{max},CSC-SC} = \left(\frac{1}{\sqrt{1 + w_{\vec{s}_{max}}^{T} H w_{\vec{s}_{max}}}}\right) \frac{\widehat{G}_{\vec{s}_{max},CSC} w_{\vec{s}_{max}}}{Y_{\vec{s}_{max},CSC}}$$

3. Form normalized steering vectors from CSC beamform and CSC-CSM using CLEAN-SC

$$\widehat{G}_{\vec{s}_{max},CSC-SC} = Y_{\vec{s}_{max},CSC}\left[\left(h_{\vec{s}_{max},CSC-SC}\right)\left(h_{\vec{s}_{max},CSC-SC}^{T}\right)\right]$$

4. Calculate CSC-SC-CSM at max location using normalized steering vectors

$$if \quad \left|\widehat{G}_{\vec{s}_{max},CSC}\right| < \left|\widehat{G}^{i}\right|$$

5. Lower CSM energy is deemed more accurate

$$\widehat{G}^{i+1} = \widehat{G}^{i} - \varphi \widehat{G}_{\vec{s}_{max},CSC-SC}$$

$$else$$

$$\widehat{G}^{i+1} = \widehat{G}^{i} - \varphi Y_{\vec{s}_{max}}^{i}\left[\left(h_{\vec{s}_{max},SC}\right)\left(h_{\vec{s}_{max},SC}^{T}\right)\right]$$

6. Update decomposed CSM accordingly

$$Stop\ if: \quad \sum\left|\widehat{G}^{i}\right| \geq \sum\left|\widehat{G}^{i-1}\right|$$

7. Stop if CSM energy increases or remains unchanged

[1]Spalt et al. 2015
[2]Spalt 2014
[3]Sijtsma 2007

Outline

1. Introduction
2. Research Methodology
3. Simulated Data Analysis
4. Experimental Data Results
5. Contributions
6. Future Work

CSC Extension to Full Array

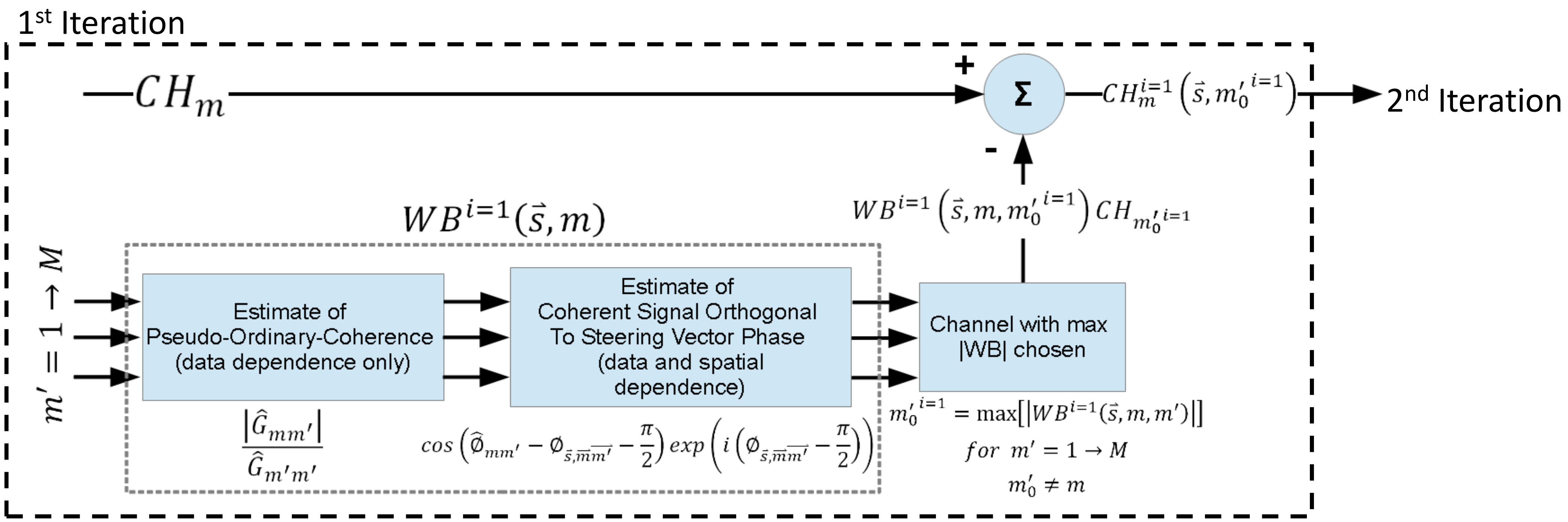
- *Optimum reference channel for use in arrays*:
    1. Maximize undesired signal cancellation
    2. Prevent amplification of noise

$$m'_0(m, \vec{s}) = \underline{max}|WB| \leq 1$$

$$m' = 1 \rightarrow M$$

$$m' \neq m$$

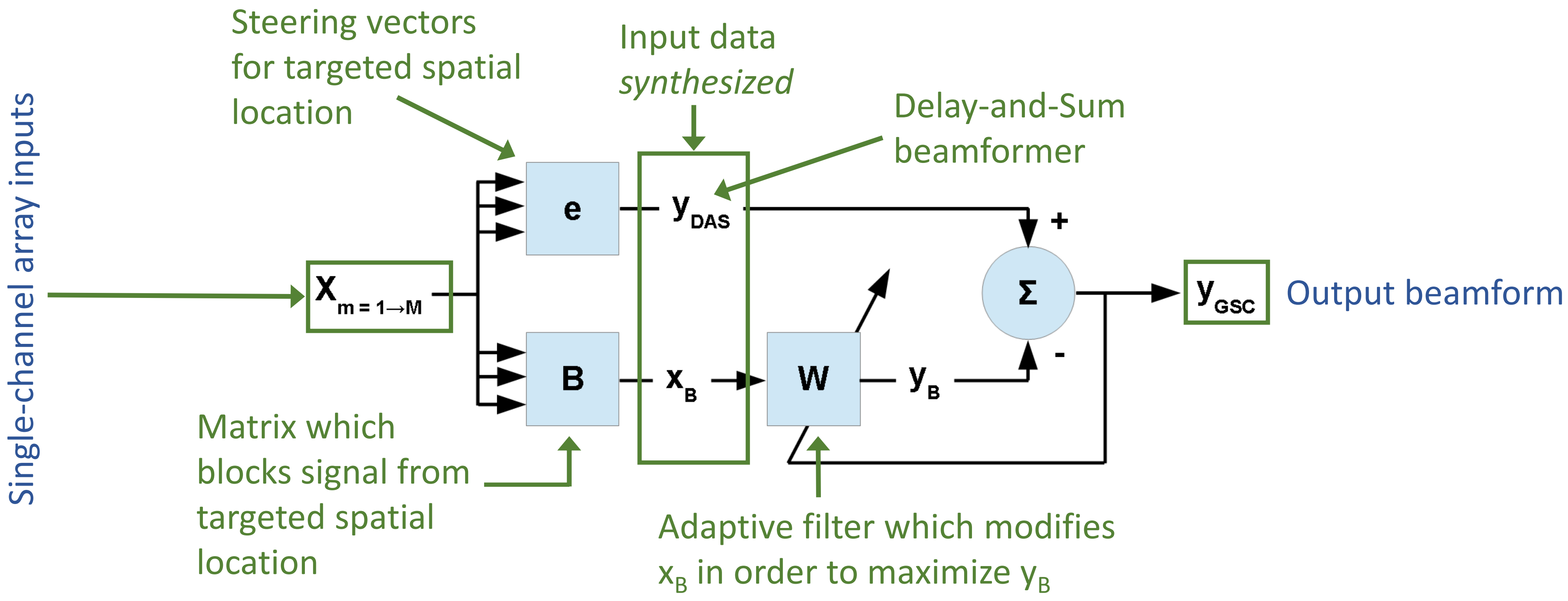
CSC Iterative Processing Algorithm



- *Stop if*:
  1. Processed channel's magnitude > channel's initial magnitude
  2. Coherent signal between channels ≤ noise floor between channels

Undesired Signal Cancellation via Spatial Filtering

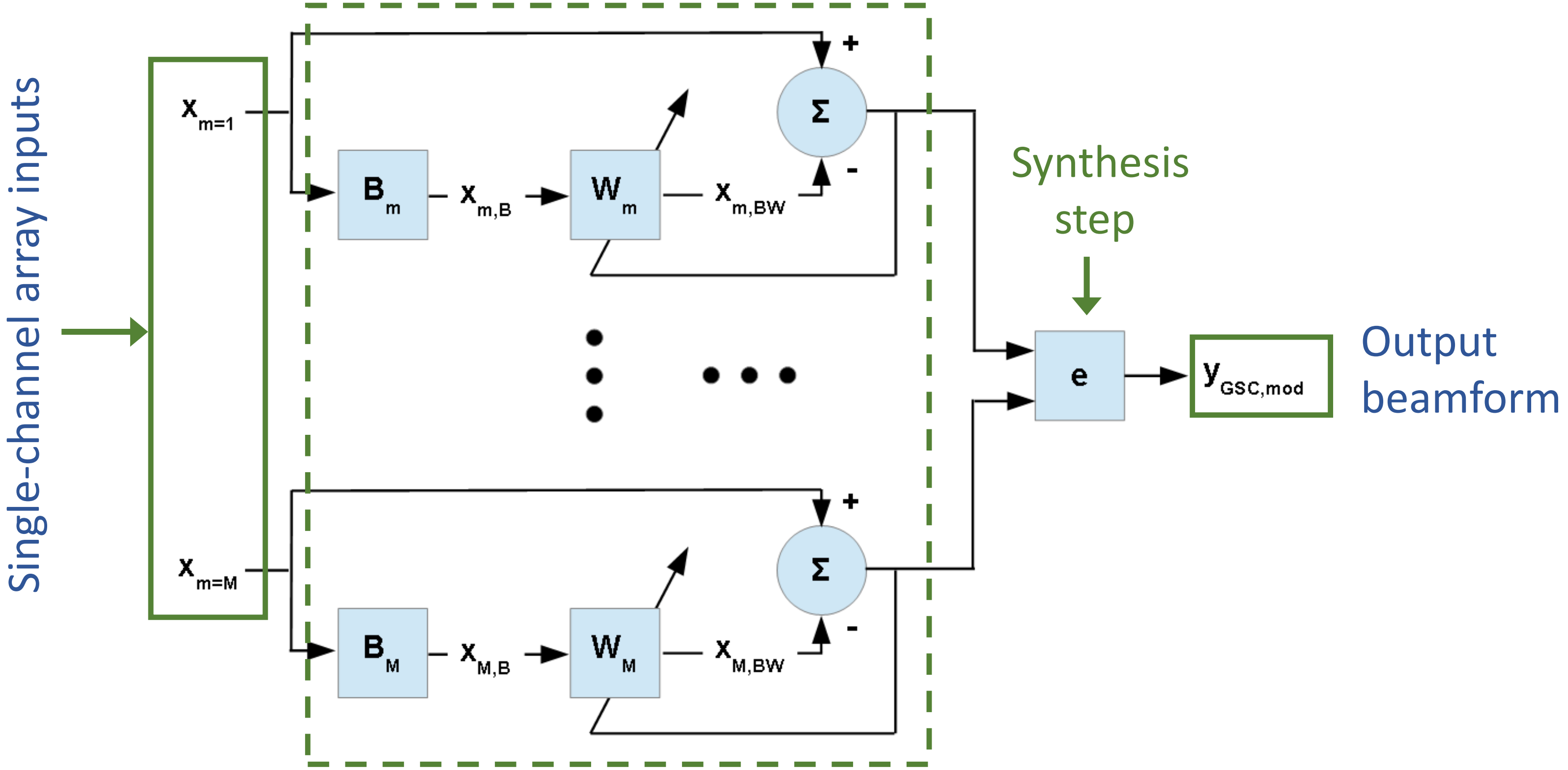
- Generalized Sidelobe Canceller (GSC)[1,2]
  - Filtering method designed to attenuate all signal except that from a user-defined point in space/direction
  - Filtering performed on the synthesized array data



[1]Hanson & Lawson 1969, [2]Griffiths & Jim 1982

Undesired Signal Cancellation via Spatial Filtering, cont.

- Modified GSC[1]



Blocking/filtering performed at the *single-channel level*

[1]Liu & Van Veen 1991

"Background Subtraction" for CSC

$$\hat{G}_{mm,background\ sub} = \hat{G}_{mm,source+flow} - \hat{G}_{mm,flow}$$

$$m = 1 \rightarrow M$$

$$if \qquad \hat{G}_{mm,background\ sub} < 0$$

$$\hat{G}_{mm,background\ sub} = \overline{\hat{G}_{mm,source+flow}}\left[\frac{1}{M'}\sum_{m=1}^{M'}\left(\hat{G}_{mm,background\ sub} > 0\right)\right]$$

$$where \qquad \overline{\hat{G}_{mm,source+flow}} = \frac{\hat{G}_{mm,source+flow}}{\frac{1}{M}\sum_{m=1}^{M}\hat{G}_{mm,source+flow}}$$

$$CH_m \quad \rightarrow \quad CH_m\sqrt{\frac{\hat{G}_{mm,background\ sub}}{\hat{G}_{mm,source+flow}}}$$