# Echo-aware signal processing for audio scene analysis

Diego Di Carlo

November 30, 2020

**PhD supervisors:** Antoine Deleforge
Nancy Bertin

**Jury members:** Laurent Girin (reviewer - president)
Simon Doclo (reviewer)
Fabio Antonacci (examiner)
Renaud Seguier (examiner)

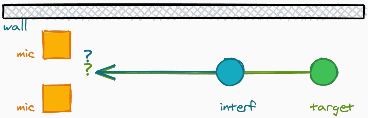
Université de Rennes 1, IRISA/INRIA, Panama research group

# Echo-aware Application

# Echo-aware Application

**Echoes = same content, different time/direction**

Image Source Model
⇔
Image Microphone Mode




Recent literature on echo-aware processing:

**What?**
Echoes = repetitions

- Sound Source Separation
  [Leglaive et al., 2016]
- Speech Enhancement
  [Flanagan et al., 1993, Dokmanić et al., 2015, **?**]

**Where?**
Echoes ← image

- Sound Source Localization
  [Ribeiro et al., 2010, Jensen et al., 2019]
- Microphone Calibration
  [Dokmanić et al., 2015, Salvati et al., 2016]
- Room Geometry Estimation

**How?**
Echoes ∈ sound propagation

- Blind Channel Estimation
  [Lin et al., 2007, Crocco et al., 2017]
- Acoustic Measurements
  [Eaton et al., 2015, Kuttruff, 2016]

# Echo-aware Application

**Echoes = same content, different time/direction**

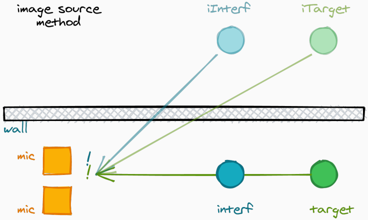



Image Source Model
⇔
Image Microphone Mode

Recent literature on echo-aware processing:

**What?**
Echoes = repetitions

- Sound Source Separation
  [Leglaive et al., 2016]
- Speech Enhancement
  [Flanagan et al., 1993, Dokmanić et al., 2015, **?**]

**Where?**
Echoes ← image

- Sound Source Localization
  [Ribeiro et al., 2010, Jensen et al., 2019]
- Microphone Calibration
  [Dokmanić et al., 2015, Salvati et al., 2016]
- Room Geometry Estimation

**How?**
Echoes ∈ sound propagation

- Blind Channel Estimation
  [Lin et al., 2007, Crocco et al., 2017]
- Acoustic Measurements
  [Eaton et al., 2015, Kuttruff, 2016]

# Echo-aware Application

## Echoes = same content, different time/direction

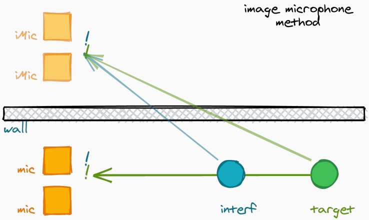



Image Source Model
⇔
Image Microphone Mode

Recent literature on echo-aware processing:

**What?**
Echoes = repetitions

- Sound Source Separation
  [Leglaive et al., 2016]
- Speech Enhancement
  [Flanagan et al., 1993, Dokmanić et al., 2015, **?**]

**Where?**
Echoes ← image

- Sound Source Localization
  [Ribeiro et al., 2010, Jensen et al., 2019]
- Microphone Calibration
  [Dokmanić et al., 2015, Salvati et al., 2016]
- Room Geometry Estimation

**How?**
Echoes ∈ sound propagation

- Blind Channel Estimation
  [Lin et al., 2007, Crocco et al., 2017]
- Acoustic Measurements
  [Eaton et al., 2015, Kuttruff, 2016]

# Echo-aware Application

**Echoes = same content, different time/direction**

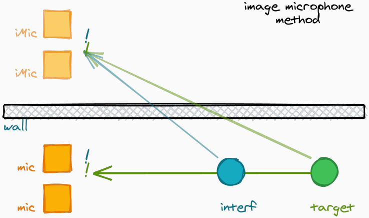



Image Source Model
⇔
Image Microphone Mode

Recent literature on echo-aware processing:

**What?**
Echoes = repetitions

- Sound Source Separation
  [Leglaive et al., 2016]
- Speech Enhancement
  [Flanagan et al., 1993, Dokmanić et al., 2015, **?**]

**Where?**
Echoes ← image

- Sound Source Localization
  [Ribeiro et al., 2010, Jensen et al., 2019]
- Microphone Calibration
  [Dokmanić et al., 2015, Salvati et al., 2016]
- Room Geometry Estimation

**How?**
Echoes ∈ sound propagation

- Blind Channel Estimation
  [Lin et al., 2007, Crocco et al., 2017]
- Acoustic Measurements
  [Eaton et al., 2015, Kuttruff, 2016]

# Echo-aware Application

**Echoes = same content, different time/direction**

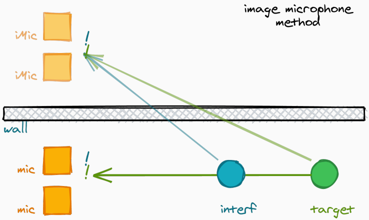



Image Source Model

$\Leftrightarrow$

Image Microphone Mode

Recent literature on echo-aware processing:

**What?**
Echoes = repetitions

- Sound Source Separation
  [Leglaive et al., 2016]
- Speech Enhancement
  [Flanagan et al., 1993,
  Dokmanić et al., 2015, **?**]

**Where?**
Echoes $\leftarrow$ image

- Sound Source Localization
  [Ribeiro et al., 2010,
  Jensen et al., 2019]
- Microphone Calibration
  [Dokmanić et al., 2015,
  Salvati et al., 2016]
- Room Geometry Estimation

**How?**
Echoes $\in$ sound propagation

- Blind Channel Estimation
  [Lin et al., 2007,
  Crocco et al., 2017]
- Acoustic Measurements
  [Eaton et al., 2015,
  Kuttruff, 2016]

# Echo-aware Application

**Echoes = same content, different time/direction**

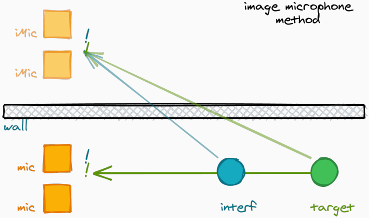



Image Source Model
⇔
Image Microphone Mode

Recent literature on echo-aware processing:

**What?**
Echoes = repetitions

- Sound Source Separation
  [Leglaive et al., 2016]
- Speech Enhancement
  [Flanagan et al., 1993, Dokmanić et al., 2015, ?]

**Where?**
Echoes ← image

- Sound Source Localization
  [Ribeiro et al., 2010, Jensen et al., 2019]
- Microphone Calibration
  [Dokmanić et al., 2015, Salvati et al., 2016]
- Room Geometry Estimation

**How?**
Echoes ∈ sound propagation

- Blind Channel Estimation
  [Lin et al., 2007, Crocco et al., 2017]
- Acoustic Measurements
  [Eaton et al., 2015, Kuttruff, 2016]

# Echo-aware Application

## Echoes = same content, different time/direction

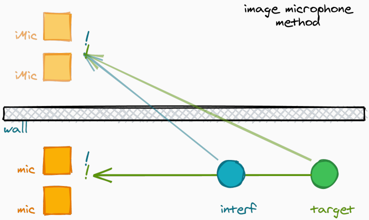



Image Source Model
⇔
Image Microphone Mode

Recent literature on echo-aware processing:

**What?**
Echoes = repetitions

- Sound Source Separation
  [Leglaive et al., 2016]
- Speech Enhancement
  [Flanagan et al., 1993, Dokmanić et al., 2015, **?**]

**Where?**
Echoes ← image

- Sound Source Localization
  [Ribeiro et al., 2010, Jensen et al., 2019]
- Microphone Calibration
  [Dokmanić et al., 2015, Salvati et al., 2016]
- Room Geometry Estimation

**How?**
Echoes ∈ sound propagation

- Blind Channel Estimation
  [Lin et al., 2007, Crocco et al., 2017]
- Acoustic Measurements
  [Eaton et al., 2015, Kuttruff, 2016]

# Echo-aware Application

**Echoes = same content, different time/direction**

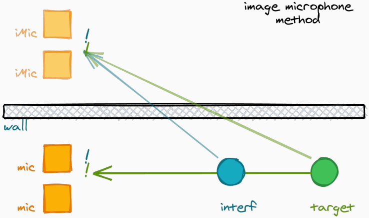



Image Source Model
⇔
Image Microphone Mode

Recent literature on echo-aware processing:

**What?**
Echoes = repetitions

- Sound Source Separation
  [Leglaive et al., 2016]
- Speech Enhancement
  [Flanagan et al., 1993, Dokmanić et al., 2015, ?]

**Where?**
Echoes ← image

- Sound Source Localization
  [Ribeiro et al., 2010, Jensen et al., 2019]
- Microphone Calibration
  [Dokmanić et al., 2015, Salvati et al., 2016]
- Room Geometry Estimation

**How?**
Echoes ∈ sound propagation

- Blind Channel Estimation
  [Lin et al., 2007, Crocco et al., 2017]
- Acoustic Measurements
  [Eaton et al., 2015, Kuttruff, 2016]

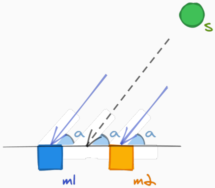
# Sound Source Localization (SSL)

(common knowledge)

**SSL** → 3D position of sound source

**SSL with 2 microphones**

- Only angle of arrival (AOA)
- can be approximated from TDOAusing e.g.GCC PHAT [Knapp and Carter, 1976]
  (known limitation, but good in practice)

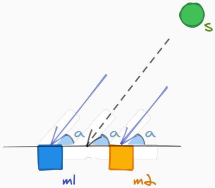


## Sound Source Localization (SSL) (common knowledge)

**SSL** $\rightarrow$ 3D position of sound source

**SSL with 2 microphones**

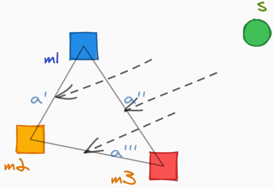
- Only angle of arrival (AOA)
- can be approximated from TDOAusing e.g.GCC PHAT [Knapp and Carter, 1976]
  (known limitation, but good in practice)




**SSL with more microphones**

- Only Directon of Arrival (DoA): azimuth (↔) and elevation (↕)

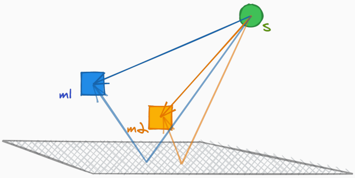
1. AOA for each pair can be “fuse” together (e.g. angular spectra in SRP-PHAT [DiBiase et al., 2001])
   (known limitation, but good in practice)



# Sound Source Localization with Echoes

**The Picnic Scenario:**

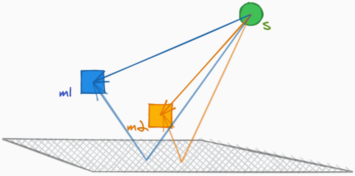
- One source
- Two microphones
  - → passive scenario
  - → generalizable to any array geometry



## Sound Source Localization with Echoes

**The Picnic Scenario:**

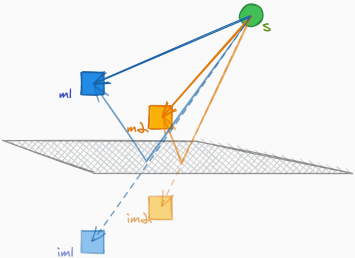
- One source
- Two microphones
  - → passive scenario
  - → generalizable to any array geometry
- Close to a very reflective surface
  - → First echo = Strongest echo
  - → $\alpha_{\text{picnic}}$ const. $\forall f$
  - → table-top device



# Sound Source Localization with Echoes

**The Picnic Scenario:**

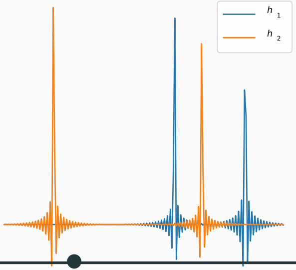
- One source
- Two microphones
  - → passive scenario
  - → generalizable to any array geometry
- Close to a very reflective surface
  - → First echo = Strongest echo
  - → $\alpha_{\text{picnic}}$ const. $\forall f$
  - → table-top device




**Each pair is augmented with echoes**

**Mirage Array**

(Microphone Array Augmetation with Echoes)

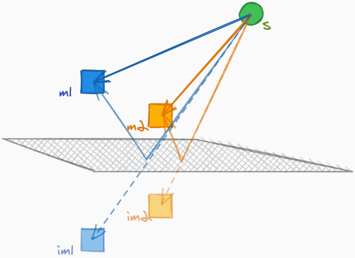



How to access the *image* microphones?

# Sound Source Localization with Echoes

**The Picnic Scenario:**

- One source
- Two microphones
  - → passive scenario
  - → generalizable to any array geometry
- Close to a very reflective surface
  - → First echo = Strongest echo
  - → $\alpha_{\text{picnic}}$ const. $\forall f$
  - → table-top device

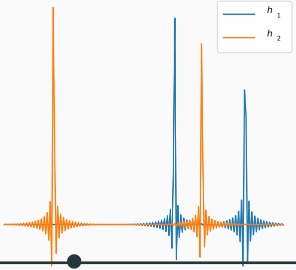



**Each pair is augmented with echoes**

**Mirage Array**

(Microphone Array Augmetation with Echoes)

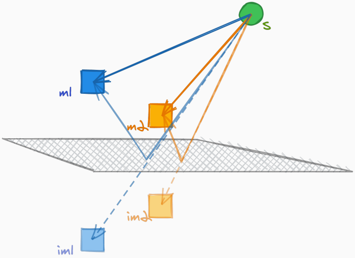
How to access the *image* microphones?



# Sound Source Localization with Echoes

**The Picnic Scenario:**

- One source
- Two microphones
  - → passive scenario
  - → generalizable to any array geometry
- Close to a very reflective surface
  - → First echo = Strongest echo
  - → $\alpha_{\text{picnic}}$ const. $\forall f$
  - → table-top device

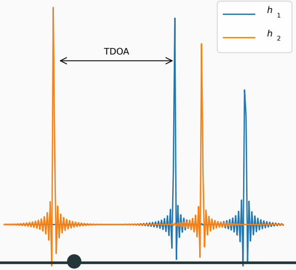



**Each pair is augmented with echoes**

**Mirage Array**

(Microphone Array Augmetation with Echoes)

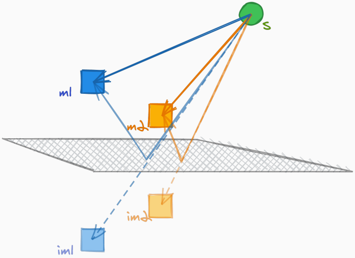
How to access the *image* microphones?



# Sound Source Localization with Echoes

### The Picnic Scenario:

- One source
- Two microphones
  - → passive scenario
  - → generalizable to any array geometry
- Close to a very reflective surface
  - → First echo = Strongest echo
  - → $\alpha_{\text{picnic}}$ const. $\forall f$
  - → table-top device

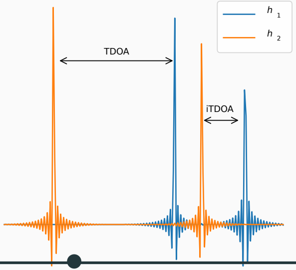



### Each pair is augmented with echoes

**Mirage Array**

(Microphone Array Augmetation with Echoes)

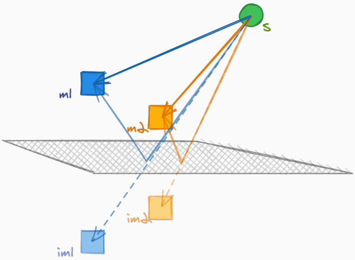
How to access the *image* microphones?



# Sound Source Localization with Echoes

### The Picnic Scenario:

- One source
- Two microphones
  - $\rightarrow$ passive scenario
  - $\rightarrow$ generalizable to any array geometry
- Close to a very reflective surface
  - $\rightarrow$ First echo = Strongest echo
  - $\rightarrow$ $\alpha_{\text{picnic}}$ const. $\forall f$
  - $\rightarrow$ table-top device

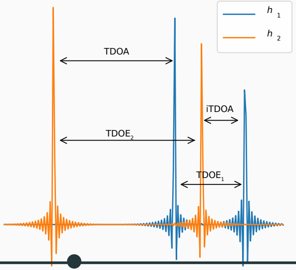



### Each pair is augmented with echoes

**Mirage Array**

(Microphone Array Augmetation with Echoes)

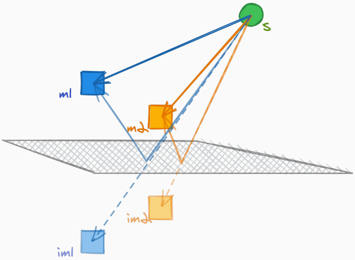
How to access the *image* microphones?



# Sound Source Localization with Echoes

**Idea:** DoA estimate on the MIRAGE array.

**Recall:** these TDOAs are the same of the DNN-based method




**Proposed Approach:**

1. use proposed MLP model for TDOAs estimation
2. fuse together the estimation ...
   - of the Mirage array (similar to SRP-PHAT[1])
   - knowing the position of the microphones;
   - use the error on a validation set as measure of uncertainty.

**Baseline:** GCC PHATon true microphones[2]

[2] [DiBiase et al., 2001]

[1] [Knapp and Carter, 1976]

# Experimental results

**Proposed:** MLP with Mirage

**Baseline:** GCC PHAT[1]

**Data:** 200 synthetic stereophonic recordings for close-surface scenario
**Metric:** accuracy in % (<10°, <20°) (also error in the manuscript)

| AOA | Input | ACCURACY $\alpha < 10°$ | $\alpha < 20°$ |
| --- | --- | --- | --- |
| Mirage | wn | 77 | 97 |
| GCC PHAT | wn | **81** | **97** |

### Observation

✓ comparable to baseline when white noise source in noiseless case

# Experimental results

**Proposed:** `MLP` with `Mirage`

**Baseline:** `GCC PHAT`[1]

**Data:** 200 synthetic stereophonic recordings for close-surface scenario
**Metric:** accuracy in % (<10°, <20°) (also error in the manuscript)

| AOA | Input | ACCURACY $\alpha < 10°$ | $\alpha < 20°$ |
|---|---|---|---|
| `Mirage` | wn | 77 | 97 |
| `Mirage` | wn+n | 26 | 54 |
| `GCC PHAT` | wn | **81** | **97** |
| `GCC PHAT` | wn+n | 65 | 83 |

## Observation

✓ comparable to baseline when white noise source in noiseless case

# Experimental results

**Proposed:** MLP with Mirage

**Baseline:** GCC PHAT[1]

**Data:** 200 synthetic stereophonic recordings for close-surface scenario

**Metric:** accuracy in % (<10°, <20°) (also error in the manuscript)

| AOA | Input | ACCURACY $\alpha < 10°$ | $\alpha < 20°$ |
|---|---|---|---|
| Mirage | wn | 77 | 97 |
| Mirage | wn+n | 26 | 54 |
| GCC PHAT | wn | **81** | **97** |
| GCC PHAT | wn+n | 65 | 83 |
| Mirage | sp | 63 | 82 |
| GCC PHAT | sp | **82** | **97** |

## Observation

✓ comparable to baseline when white noise source in noiseless case

# Experimental results

**Proposed:** `MLP` with `Mirage`

**Baseline:** `GCC PHAT`[1]

**Data:** 200 synthetic stereophonic recordings for close-surface scenario
**Metric:** accuracy in % (<10°, <20°) (also error in the manuscript)

| AOA | Input | ACCURACY $\alpha < 10°$ | ACCURACY $\alpha < 20°$ |
|---|---|---|---|
| Mirage | wn | 77 | 97 |
| Mirage | wn+n | 26 | 54 |
| GCC PHAT | wn | **81** | **97** |
| GCC PHAT | wn+n | 65 | 83 |
| Mirage | sp | 63 | 82 |
| Mirage | sp+n | 16 | 35 |
| GCC PHAT | sp | **82** | **97** |
| GCC PHAT | sp+n | 19 | 32 |

## Observation

✓ comparable to baseline when white noise source in noiseless case
✗ not generalize to noisy and speech data

# Experimental results

**Proposed:** MLP with Mirage

**Baseline:** GCC PHAT[1]

**Data:** 200 synthetic stereophonic recordings for close-surface scenario

**Metric:** accuracy in % ($<10°$, $<20°$) (also error in the manuscript)

| AOA | Input | ACCURACY $\alpha < 10°$ | ACCURACY $\alpha < 20°$ |
|---|---|---|---|
| Mirage | wn | 77 | 97 |
| Mirage | wn+n | 26 | 54 |
| GCC PHAT | wn | **81** | **97** |
| GCC PHAT | wn+n | 65 | 83 |
| Mirage | sp | 63 | 82 |
| Mirage | sp+n | 16 | 35 |
| GCC PHAT | sp | **82** | **97** |
| GCC PHAT | sp+n | 19 | 32 |

| DoA | Input | ACCURACY $< 10°$ $\theta$ | ACCURACY $< 10°$ $\phi$ | ACCURACY $< 20°$ $\theta$ | ACCURACY $< 20°$ $\phi$ |
|---|---|---|---|---|---|
| Mirage | wn | **59** | **71** | **79** | **88** |
| Mirage | wn+n | 18 | 26 | 35 | 66 |
| Mirage | sp | 45 | 59 | 71 | 83 |
| Mirage | sp+n | 17 | 12 | 38 | 43 |

## Observation

- ✓ comparable to baseline when white noise source in noiseless case
- ✗ not generalize to noisy and speech data
- ✓ Solved "impossible" localization

# Experimental results

**Proposed:** MLP with Mirage

**Baseline:** GCC PHAT[1]

**Data:** 200 synthetic stereophonic recordings for close-surface scenario
**Metric:** accuracy in % ($<10°$, $<20°$) (also error in the manuscript)

| AOA | Input | ACCURACY $\alpha < 10°$ | ACCURACY $\alpha < 20°$ |
|---|---|---|---|
| Mirage | wn | 77 | 97 |
| Mirage | wn+n | 26 | 54 |
| GCC PHAT | wn | **81** | **97** |
| GCC PHAT | wn+n | 65 | 83 |
| Mirage | sp | 63 | 82 |
| Mirage | sp+n | 16 | 35 |
| GCC PHAT | sp | **82** | **97** |
| GCC PHAT | sp+n | 19 | 32 |

| DoA | Input | ACCURACY $< 10°$ $\theta$ | ACCURACY $< 10°$ $\phi$ | ACCURACY $< 20°$ $\theta$ | ACCURACY $< 20°$ $\phi$ |
|---|---|---|---|---|---|
| Mirage | wn | **59** | **71** | **79** | **88** |
| Mirage | wn+n | 18 | 26 | 35 | 66 |
| Mirage | sp | 45 | 59 | 71 | 83 |
| Mirage | sp+n | 17 | 12 | 38 | 43 |

## Observation

- ✓ comparable to baseline when white noise source in noiseless case
- ✗ not generalize to noisy and speech data
- ✓ Solved “impossible” localization
- ⚠ Performance depending on echo estimation methods

5

# References i


Crocco, M., Trucco, A., and Del Bue, A. (2017).
**Uncalibrated 3d room geometry estimation from sound impulse responses.**
*Journal of the Franklin Institute*, 354(18):8678–8709.

DiBiase, J. H., Silverman, H. F., and Brandstein, M. S. (2001).
**Robust localization in reverberant rooms.**
In *Microphone Arrays*, pages 157–180. Springer.

Dokmanić, I., Scheibler, R., and Vetterli, M. (2015).
**Raking the cocktail party.**
*IEEE journal of selected topics in signal processing*, 9(5):825–836.

Eaton, J., Gaubitch, N. D., Moore, A. H., and Naylor, P. A. (2015).
**The ace challenge—corpus description and performance evaluation.**
In *2015 IEEE Workshop on Applications of Signal Processing to Audio and Acoustics (WASPAA)*, pages 1–5. IEEE.

Evers, C. and Naylor, P. A. (2018).
**Acoustic slam.**
*IEEE/ACM Transactions on Audio, Speech, and Language Processing*, 26(9):1484–1498.

Flanagan, J. L., Surendran, A. C., and Jan, E.-E. (1993).
**Spatially selective sound capture for speech and audio processing.**
*Speech Communication*, 13(1-2):207–222.

Jensen, J. R., Saqib, U., and Gannot, S. (2019).
**An em method for multichannel toa and doa estimation of acoustic echoes.**
In *2019 IEEE Workshop on Applications of Signal Processing to Audio and Acoustics (WASPAA)*, pages 120–124. IEEE.

Knapp, C. and Carter, G. (1976).
**The generalized correlation method for estimation of time delay.**
*IEEE transactions on acoustics, speech, and signal processing*, 24(4):320–327.

Kreković, M., Dokmanić, I., and Vetterli, M. (2016).
**Echoslam: Simultaneous localization and mapping with acoustic echoes.**
In *2016 IEEE International Conference on Acoustics, Speech and Signal Processing (ICASSP)*, pages 11–15. Ieee.

Kuttruff, H. (2016).
***Room acoustics.***
CRC Press.

Leglaive, S., Badeau, R., and Richard, G. (2016).
**Multichannel audio source separation with probabilistic reverberation priors.**
*IEEE/ACM Transactions on Audio, Speech, and Language Processing*, 24(12):2453–2465.

Lin, Y., Chen, J., Kim, Y., and Lee, D. D. (2007).
**Blind sparse-nonnegative (bsn) channel identification for acoustic time-difference-of-arrival estimation.**
In *2007 IEEE Workshop on Applications of Signal Processing to Audio and Acoustics*, pages 106–109. IEEE.

# References iv

Ribeiro, F., Ba, D., Zhang, C., and Florêncio, D. (2010).
**Turning enemies into friends: Using reflections to improve sound source localization.**
In *2010 IEEE International Conference on Multimedia and Expo*, pages 731–736. IEEE.

Salvati, D., Drioli, C., and Foresti, G. L. (2016).
**Sound source and microphone localization from acoustic impulse responses.**
*IEEE Signal Processing Letters*, 23(10):1459–1463.