A Probability Model for Interaural Phase Difference

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Outline

Introduction

Probability model
- Observations

Experiments
- Results

Summary

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Probability model

Observations

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Summary

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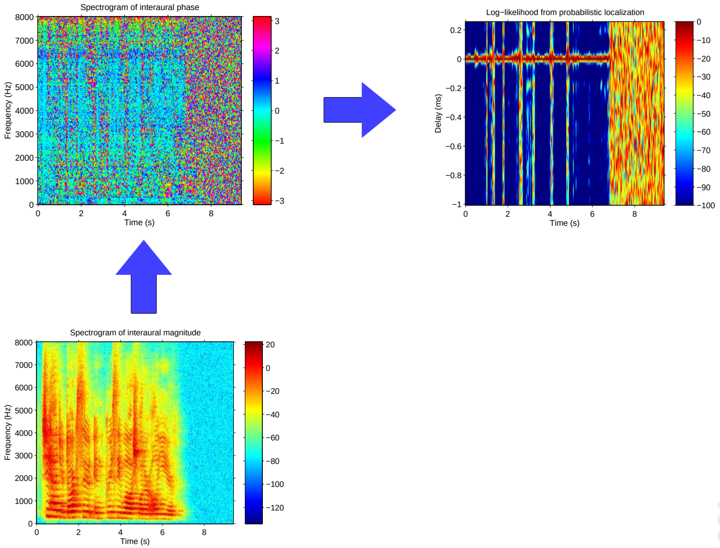
Vision

- Computer programs that can hear as well as people can
- In a room with two mics and multiple people talking
  - Locate the sound sources in space
  - Characterize the room
  - Determine what is said

Overview

- Problem: localization, time delay of arrival estimation
  - Stereo recording
  - Single source
  - Reverberation or additive noise
- Solution: probability model for interaural phase difference in reverberation
  - Considers time-frequency points individually, IID
  - No assumptions about source characteristics
- Performance: estimates delay more accurately than generalized cross-correlation in simulations

Probabilistic localization



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Previous work

- Knapp and Carter (1976)
  - Generalized cross correlation and PHAse Transform
  - Maximum likelihood estimator for stationary sources in uncorrelated noise
- Stern and Trahiotis (1995)
  - Based more on human perception
  - Cross-correlations in many frequency bands
  - “Straightness” measure for combining bands
- Rennie (2005)
  - EM algorithm for localizing multiple sources based on whole STFT frames

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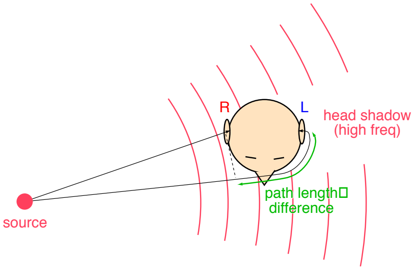
Data

- Speech from TIMIT database
  - Phonetically balanced sentences from 630 native English speakers
  - "She had your dark suit in greasy wash water..."
- Binaural room impulse responses from Shinn-Cunningham et al. (2005)
  - Recorded with KEMAR manikin in classroom
  - 4 locations, 7 directions, 3 distances, 3 repetitions
  - "She had your dark suit in greasy wash water..."
- Binaural anechoic impulse responses from Algazi et al. (2001)
  - Recorded with KEMAR manikin in anechoic chamber
  - 25 azimuths, 50 elevations
  - Speech-shaped noise added at 10 dB, direct to reverb ratio
  - "She had your dark suit in greasy wash water..."

Listening model

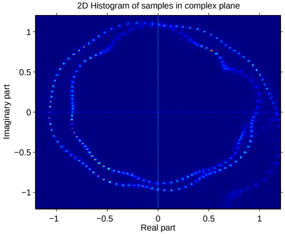


$$\ell(t) = a_\ell s(t - \tau_\ell) * n_\ell(t)$$
$$r(t) = a_r s(t - \tau_r) * n_r(t)$$

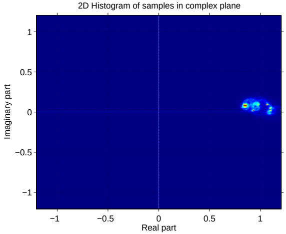
$$N(j\omega) = e^{-a + j\omega\tau} \frac{L(j\omega)}{R(j\omega)}$$

- Delay between channels because of path difference
- Gain between channels because of head shadowing
- Convolutive noise to model reverberation
- Noise assumed to be compact

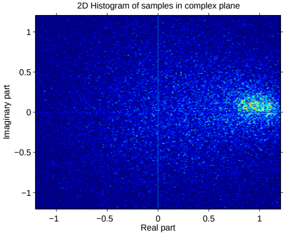
Noise distributions in the complex plane



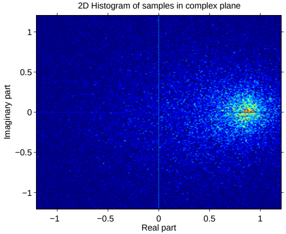
Incorrect τ



Anechoic



Additive



Reverberant

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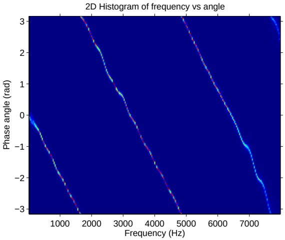
Phase of noise vs frequency



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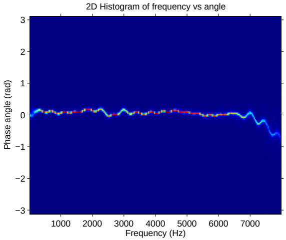

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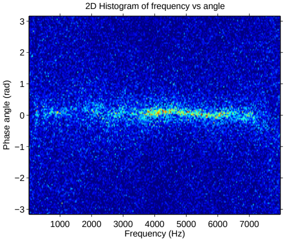
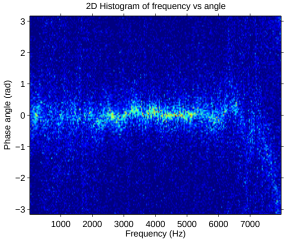
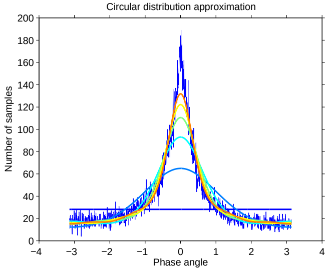


Additive



Reverberant

Probability model



$$p(\Delta\phi \,|\, \omega\tau) = \exp\left(\sum_k a_k \cos^k(\Delta\phi - \omega\tau)\right)$$

- Circular maximum entropy probability distribution
- Fourier series gives desired moments

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Experiments

- Compare PHAT to probabilistic method
- Compare sensitivity of probabilistic method to learned noise distribution
- Test in simulated reverberation and additive noise, at varying azimuths
- Pool probabilistic estimates over frequency to compare to PHAT
- Measure average error in delay estimate as a function of pooling over time

PHAse Transform (PHAT)

Classical Time-Delay of Arrival (TDOA) estimator

Cross-correlation:

$$\hat{\tau} = \arg\max_{\tau} \ell(t) * r(-t)$$

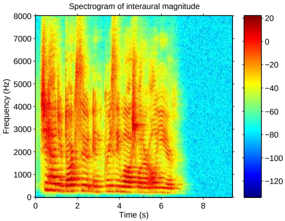
Generalized cross-correlation:

$$\hat{\tau} = \arg\max_{\tau} \sum_{\omega} \psi(j\omega) L(j\omega) R^*(j\omega) e^{j\omega\tau}$$

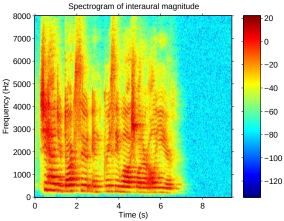
e.g. PHAse Transform:

$$\hat{\tau} = \arg\max_{\tau} \sum_{\omega} \frac{1}{|L(j\omega)||R(j\omega)|} L(j\omega) R^*(j\omega) e^{j\omega\tau}$$

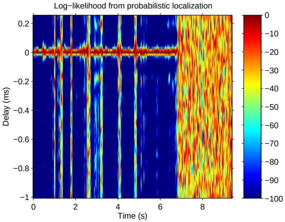
Example localizations



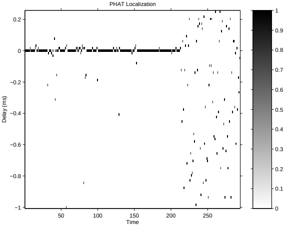
Speech signal



Speech signal



Probabilistic localization



PHAT localization

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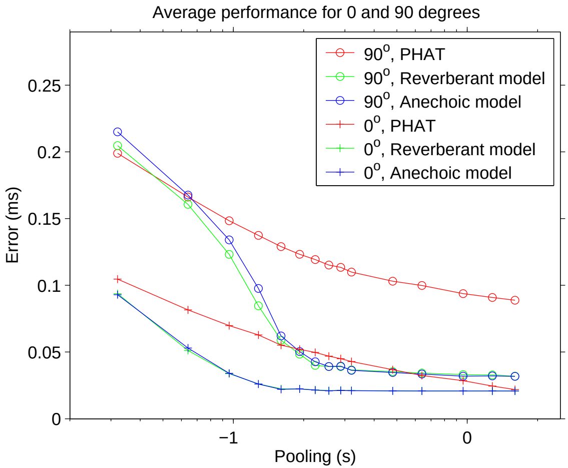
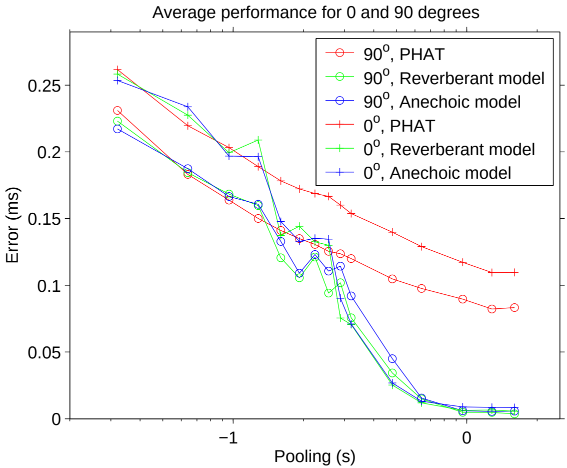
Results in reverberation



Results in additive noise



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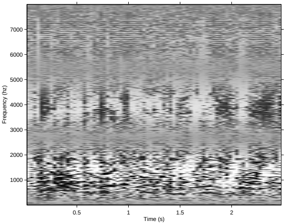
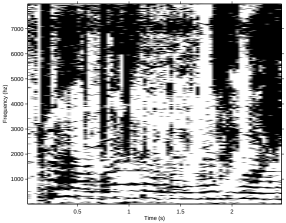
Summary

- Probabilistic model of phase at individual interaural spectrogram points
- Estimates true delays better than PHAT in reverberation
- Estimates true delays as well as, if not better than, PHAT in additive noise
- Makes no assumptions about the sources involved
- Allows powerful analyses, e.g. likelihoods of delays over arbitrary regions of spectrogram
- Lends itself to localizing multiple sources

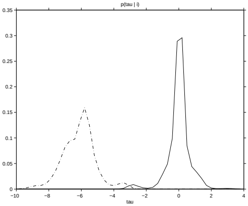
EM Algorithm



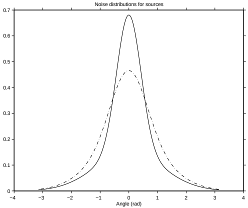
EM separation



Ground truth



$p(\tau \mid i)$



$p(\Delta\phi - \omega\tau \mid i)$

Thank you

Any questions?

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