

# IRISA/D5 Thematic Seminar

## Source classification

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## Audio source separation vs classification

Audio scenes can be quite complex but **source separation** has progressed in the last few years!

Music 



Vocals 

Home automation 



Spoken command 

TV series 



Speech 

Can this help audio “**classification**” tasks such as

- speaker/singer identification,
- speech/lyrics transcription,
- music genre classification, keyword spotting, multimedia indexing?

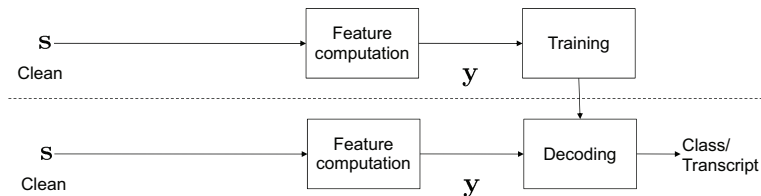
- 1 Single-source audio classification
- 2 The uncertainty handling paradigm
- 3 Uncertainty estimation
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## Audio classification

Audio content description techniques do not operate directly on the input signal but on derived **features**.

Classification/transcription most often relies on probabilistic **acoustic models** of the features.

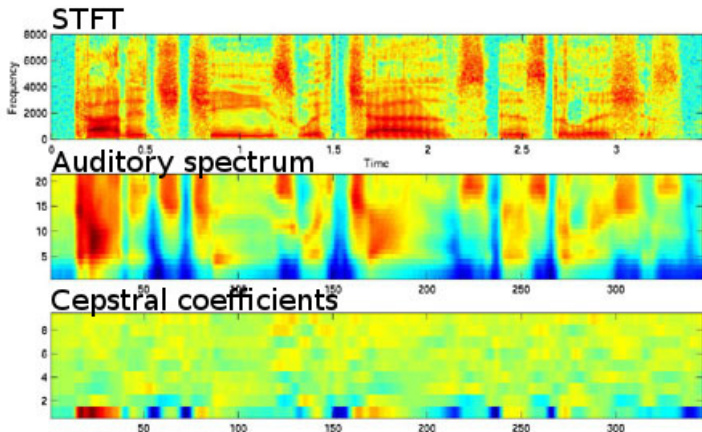
Two stages: **training** and **decoding**.



The characteristics of **training and test data must match** each other.

# Mel-frequency cepstral coefficients

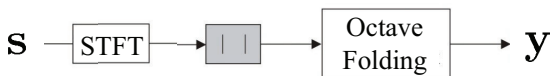
MFCCs represent the auditory spectral envelope on short time frames.



from Ellis, 2005

# Chroma coefficients

**Chroma coefficients** represent the pitch content of sound on short time frames.



## Other features

For speech:

- $\Delta$ MFCC and  $\Delta\Delta$ MFCC,
- perceptual linear prediction (PLP) coefficients,
- spectro-temporal modulation features,
- neural network features,
- ...

For music:

- all of the above,
- rhythm features,
- ...

## GMM acoustic models

Classification tasks can be addressed using **Gaussian mixture acoustic models** (GMM).

For a given class  $C$ , the corresponding GMM is parameterized by

- mean vectors  $\boldsymbol{\mu}_i$
- covariance matrices  $\boldsymbol{\Sigma}_i$
- weights  $\omega_i$ .

Classification is performed in the maximum a posteriori (MAP) sense: choose the class  $C$  that maximizes

$$p(C)p(\mathbf{y}|C) = p(C) \prod_n \sum_i \omega_i \mathcal{N}(\mathbf{y}_n | \boldsymbol{\mu}_i, \boldsymbol{\Sigma}_i).$$

Training is performed in the maximum likelihood (ML) sense using an EM algorithm.



# HMM acoustic models

Transcription tasks are addressed using [hidden Markov acoustic models \(HMM\)](#) with Gaussian observation probabilities.

For speech, these probabilities encode knowledge about word pronunciations and word sequences.

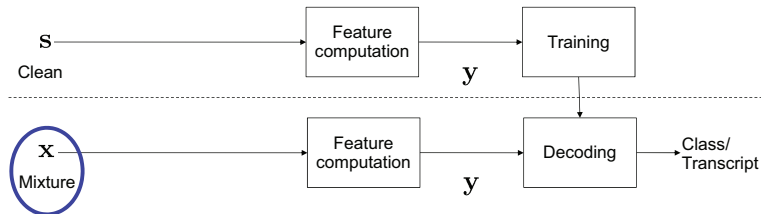
Training and testing rely on similar equations as for GMMs, except that the computed GMM likelihood values are post-processed using transition probabilities.

We focus for simplicity on GMMs in the following. The techniques presented here easily extend to HMMs with GMM observation probabilities.

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# Training/test mismatch

The matched training/test paradigm becomes invalid on multi-source or noisy data.



How can we reduce or circumvent the mismatch?

# Mismatch circumvention techniques

General techniques include:

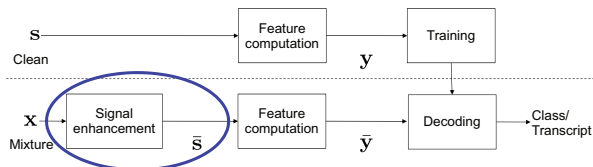
- using different features (modulation features, RNN, etc),
- changing the training objective (discriminative, ARD, etc),
- combining the outputs of several systems,
- ...

These non-specific techniques partly circumvent the mismatch between training and test data.

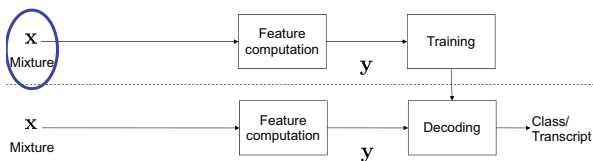
We focus on specific techniques directly aiming to reduce it instead.

# Conventional mismatch reduction techniques

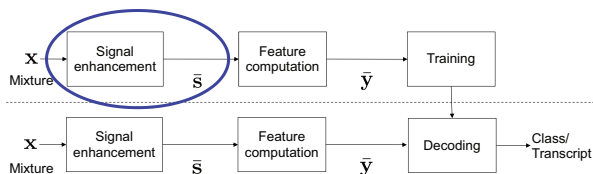
**Feature compensation:**  
good separation but often increased mismatch



**Training data coverage:**  
better match but huge training set needed



**Noise adaptive training**  
[Deng, 2000]: combines both advantages, large training set still needed



# The uncertainty handling paradigm

Emerging paradigm: estimate and propagate confidence values represented by (approximate) **posterior distributions**.

Early focus on Boolean uncertainty did not allow complex features.

More recent focus on **Gaussian** distributions [Deng, Astudillo, Kolossa. . .].

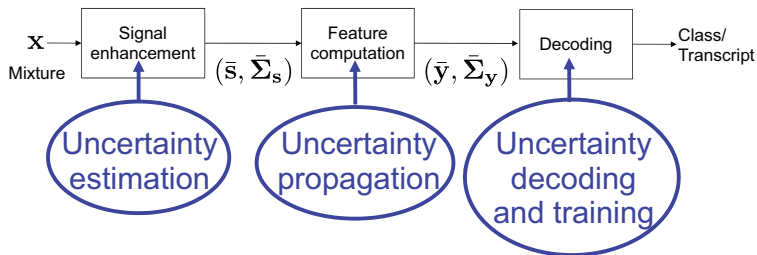


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## Reminder about audio source separation

Audio source separation techniques typically operate in the **time-frequency** domain, e.g., via the short time Fourier transform (STFT).

They often rely on probabilistic **parametric models** of the source signals and the mixing process with parameters such as:

- steering/blocking vectors for beamforming, ICA,
- basis spectra and scaling coefficients for NMF, harmonic NMF, and variants thereof,
- exemplar spectra and discrete hidden states for GMM, HMM...

Flexible FASST toolbox integrating several of the above models.  
<http://bass-db.gforge.inria.fr/fasst/>

# Heuristic uncertainty estimator

First idea: the bigger the change, the bigger the uncertainty [Kolossa].

Variance of  $p(\mathbf{s}|\mathbf{x})$  proportional to the squared difference between the noisy signal  $\mathbf{x}$  and the separated signal  $\bar{\mathbf{s}}$ :

$$\bar{\Sigma}_{\mathbf{s},nf} = \text{diag}(\alpha_f |\mathbf{x}_{nf} - \bar{\mathbf{s}}_{nf}|^2).$$

Heuristic solution, not very elegant but somewhat effective.

## Wiener uncertainty estimator

Second idea: uncertainty stemming from the [Wiener filter](#) [Astudillo].

First estimate the parameters  $\theta$  of the source models in the maximum likelihood (ML) sense

$$\hat{\theta} = \arg \max p(\mathbf{x}|\theta).$$

Then, assuming that  $\mathbf{x}$  and  $\mathbf{s}$  are Gaussian with covariances depending on  $\theta$ , we have

$$p(\mathbf{s}|\mathbf{x}) \approx p(\mathbf{s}|\mathbf{x}, \hat{\theta}) = \prod_{nf} \mathcal{N}(\mathbf{s}_{nf} | \bar{\mathbf{s}}_{nf}, \bar{\boldsymbol{\Sigma}}_{\mathbf{s},nf})$$

with

$$\begin{aligned} \bar{\mathbf{s}}_{nf} &= \boldsymbol{\Sigma}_{\mathbf{s},nf} \boldsymbol{\Sigma}_{\mathbf{x},nf}^{-1} \mathbf{x}_{nf} \\ \bar{\boldsymbol{\Sigma}}_{\mathbf{s},nf} &= (\mathbf{I} - \boldsymbol{\Sigma}_{\mathbf{s},nf} \boldsymbol{\Sigma}_{\mathbf{x},nf}^{-1}) \boldsymbol{\Sigma}_{\mathbf{s},nf} \end{aligned}$$

More principled, but does not account for the uncertainty about  $\theta$  itself!

# Bayesian uncertainty estimator (1)

The theoretical **Bayesian uncertainty estimator** is given by [Adiloğlu]

$$p(\mathbf{s}|\mathbf{x}) = \int p(\mathbf{s}, \theta|\mathbf{x}) d\theta$$

Problem: this integral typically involves thousands of dimensions!

**Variational Bayes** (VB): approximate the joint posterior  $p(\mathbf{s}, \theta|\mathbf{x})$  by the closest distribution  $q(\mathbf{s}, \theta)$  for which the integral is tractable.

When  $q$  is assumed to factor as  $q(\mathbf{s}, \theta) = q(\mathbf{s})q(\theta)$ , the posterior over  $\mathbf{s}$  is simply obtained as

$$p(\mathbf{s}|\mathbf{x}) \approx q(\mathbf{s}).$$

## Bayesian uncertainty estimator (2)

Minimizing the Kullback-Leibler divergence between  $p$  and  $q$  is equivalent to maximizing the so-called variational free energy

$$\mathcal{L}(q) = \int q(\mathbf{s}, \theta) \log \frac{p(\mathbf{x}, \mathbf{s}, \theta)}{q(\mathbf{s}, \theta)} d\mathbf{s} d\theta$$

This quantity is sometimes not maximizable in closed form: minorization by a parametric bound  $f(\mathbf{x}, \mathbf{s}, \theta, \Omega) \leq p(\mathbf{x}, \mathbf{s}, \theta)$  may be needed.

Assuming  $q(\mathbf{s}, \theta) = \prod_{nf} q(\mathbf{s}_{nf}) \prod_i q(\theta_i)$ , the solution is iteratively estimated by

- 1 tightening the bound w.r.t. the variational parameters  $\Omega$ ,
- 2  $q(\theta_i) \propto \exp[\mathbb{E}_{\mathbf{s}, \theta_{i' \neq i}} \log f(\mathbf{x}, \mathbf{s}, \theta, \Omega)]$
- 3  $q(\mathbf{s}_{nf}) \propto \exp[\mathbb{E}_{\mathbf{s}_{n' f' \neq nf}, \theta} \log f(\mathbf{x}, \mathbf{s}, \theta, \Omega)]$

## Bayesian uncertainty estimator (3)

This results in an **expectation-maximization (EM)**-like source separation algorithm where posterior distributions over the parameters are updated instead of point estimates as in usual ML-based EM.

Resulting approximating distributions for FASST:

- complex-valued Gaussian for  $\mathbf{s}_{nf}$  and for the steering vectors,
- generalized inverse Gaussian for the NMF parameters.

# Speaker identification benchmark (1)

CHiME Speech Separation and Recognition Challenge  
[http://spandh.dcs.shef.ac.uk/chime\\_challenge/](http://spandh.dcs.shef.ac.uk/chime_challenge/)

Data: short spoken commands mixed with genuine noise backgrounds recorded in a family home.

Training: 20 clean utterances from each of 34 speakers

Test: 20 other utterances per speaker, each mixed at 6 different SNRs

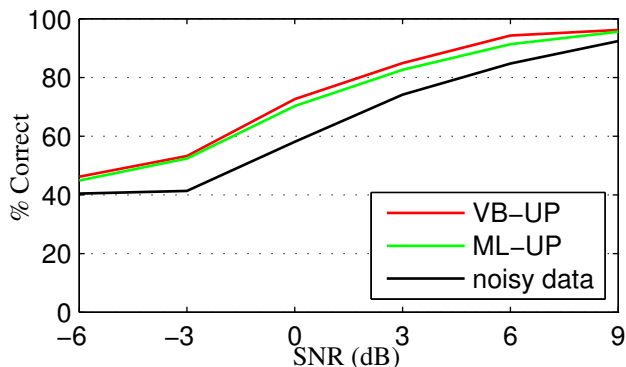
Enhancement: multichannel NMF (ML or VB).

Features: static MFCCs (2 to 20), log-normal uncertainty propagation

Baseline classifier: 32-component GMMs with diagonal covariances, initialized by hierarchical K-means

## Speaker identification benchmark (2)

VB performs similarly to ML for the estimation of  $\bar{s}$ , but it results in better  $\bar{\Sigma}_s$  and eventually in improved speaker identification accuracy.





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## Mel frequency cepstral coefficients

We take the example of **Mel frequency cepstral coefficients** (MFCCs):



General idea: split the computation into simple steps and propagate the posterior through each step [Gales, Astudillo].

Approximate closed-form equations are preferred to sampling techniques because of their smaller computational cost.

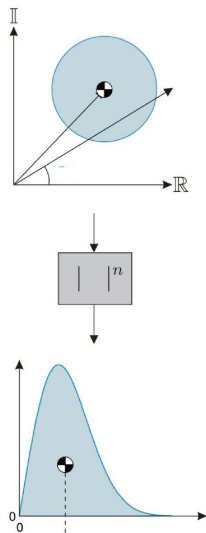
Similar equations can be reused for other features (RASTA-PLP, MLP, chroma, etc).

# Propagation through a linear transform

The Mel filterbank and the DCT are linear transforms.

$$\begin{aligned}\overline{\mathbf{Az}} &= \mathbf{A}\bar{\mathbf{z}} \\ \bar{\Sigma}_{\mathbf{Az}} &= \mathbf{A}\bar{\Sigma}_{\mathbf{z}}\mathbf{A}^H\end{aligned}$$

# Propagation through the magnitude transform



Phase integration results in a Rice distribution whose first and second order moments can be computed in closed form.

$$\overline{|z|} = \bar{\sigma}_z \sqrt{\pi/2} L_{1/2}(-|\bar{z}|^2/2\bar{\sigma}_z^2)$$

$$\bar{\sigma}_{|z|}^2 = |\bar{z}|^2 + 2\bar{\sigma}_z^2 - \overline{|z|}^2$$

with  $L_{1/2}(z) = e^{z/2} [(1-z)l_0(-z/2) - z l_1(-z/2)]$ .

from Astudillo, 2012

## Propagation through the log transform

The exponential transform results in a distribution whose first and second order moments can be computed by closed form equations.

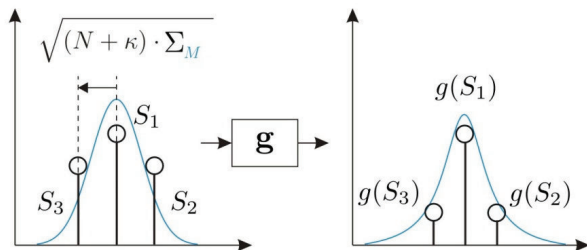
The inversion of these equations yields a good approximation for the logarithmic transform.

$$\overline{\log z_i} = \log(\bar{z}_i) - \frac{1}{2} \log \left( \frac{\bar{\Sigma}_{z,ii}}{\bar{z}_i^2} + 1 \right)$$

$$\bar{\Sigma}_{\log z,ij} = \log \left( \frac{\bar{\Sigma}_{z,ij}}{\bar{z}_i \bar{z}_j} + 1 \right)$$

## Propagation through general nonlinear transforms

For general nonlinear transforms, the unscented transform often yields a good approximation at the fraction of the cost of a full sampling scheme.



from Astudillo, 2012

Vector Taylor series (VTS) has also been proposed.

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# Uncertainty decoding

For noisy data, classification can be performed via the **uncertainty decoding** (UD) rule [Deng]

$$\begin{aligned} p(\bar{\mathbf{y}}, \bar{\boldsymbol{\Sigma}} | C) &\approx \int p(\mathbf{y} | \bar{\mathbf{y}}, \bar{\boldsymbol{\Sigma}}) p(\mathbf{y} | C) d\mathbf{y} \\ &= \prod_n \sum_i \omega_i \mathcal{N}(\bar{\mathbf{y}}_n | \boldsymbol{\mu}_i, \boldsymbol{\Sigma}_i + \bar{\boldsymbol{\Sigma}}_n) \end{aligned}$$

Model and noise variances add up: this exploits both the model and the uncertainty to (implicitly) predict the missing data.



# Uncertainty training (1)

So far, we have assumed that the GMMs have been trained on clean data but clean data may not be available!

Retraining on noisy data allows to learn the residual distortion that  $\bar{\Sigma}_n$  failed to represent because

- the Gaussian parametric model of uncertainty may not fit the actual distribution of uncertainty,
- even when it does, its covariance  $\bar{\Sigma}_n$  is never perfectly estimated.

To do so, we maximize the UD criterion over the training data via an EM algorithm considering both the states  $i_n$  and the clean data  $\mathbf{y}_n$  as hidden data [Ozerov].

## Uncertainty training (2)

E-step: estimate clean feature moments by Wiener filtering

$$\begin{aligned}\gamma_{i,n} &\propto \omega_i \mathcal{N}(\bar{\mathbf{y}}_n | \boldsymbol{\mu}_i, \boldsymbol{\Sigma}_i + \bar{\boldsymbol{\Sigma}}_n), \\ \hat{\mathbf{y}}_{i,n} &= \boldsymbol{\mu}_i + \boldsymbol{\Sigma}_i (\boldsymbol{\Sigma}_i + \bar{\boldsymbol{\Sigma}}_n)^{-1} (\bar{\mathbf{y}}_n - \boldsymbol{\mu}_i), \\ \hat{\mathbf{R}}_{yy,i,n} &= \hat{\mathbf{y}}_{i,n} \hat{\mathbf{y}}_{i,n}^T + (\mathbf{I} - \boldsymbol{\Sigma}_i (\boldsymbol{\Sigma}_i + \bar{\boldsymbol{\Sigma}}_n)^{-1}) \boldsymbol{\Sigma}_i.\end{aligned}$$

M-step: update GMM parameters

$$\begin{aligned}\omega_i &= \frac{1}{N} \sum_{n=1}^N \gamma_{i,n}, \\ \boldsymbol{\mu}_i &= \frac{1}{\sum_{n=1}^N \gamma_{i,n}} \sum_{n=1}^N \gamma_{i,n} \hat{\mathbf{y}}_{i,n}, \\ \boldsymbol{\Sigma}_i &= \text{diag} \left( \frac{1}{\sum_{n=1}^N \gamma_{i,n}} \sum_{n=1}^N \gamma_{i,n} \hat{\mathbf{R}}_{yy,i,n} - \boldsymbol{\mu}_i \boldsymbol{\mu}_i^T \right).\end{aligned}$$

## Speaker identification benchmark

Same data, source separation algorithm and baseline classifier as above, heuristic STFT uncertainty estimation + log-normal propagation.

Results averaged into 4 training conditions:

- clean,
- matched (same SNR),
- unmatched (different SNR),
- multicondition (all SNRs, hence more noisy data)

Enhanced signal	Training approach	Decoding approach	Training condition			
			Clean	Matched	Unmatched	Multi
No	Conventional	Conventional	65.17	71.81	69.34	84.09
Yes	Conventional	Conventional	55.22	82.11	80.91	90.12
Yes	Conventional	Uncertainty				
Yes	Uncertainty	Uncertainty				

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Yes	Conventional	Uncertainty	<b>75.51</b>	78.60	77.58	85.02
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Yes	Conventional	Uncertainty	<b>75.51</b>	78.60	77.58	85.02
Yes	Uncertainty	Uncertainty	<b>75.51</b>	<b>82.87</b>	<b>81.52</b>	<b>91.13</b>

## Singer identification benchmark

Data: 40 songs by 10 singers (5 male and 5 female) from the RWC Popular Music Database, split into 10 s segments

Training/testing: data organized into 4 training/testing folds

Enhancement: melody separation algorithm by Durrieu et al.

Features: static MFCCs (2 to 20), VTS propagation

Baseline classifier: 32-component GMMs with diagonal covariances

Accuracy (%)	per 10 s singing segment					per song (maj. vote)	
	Fold 1	Fold 2	Fold 3	Fold 4	Total	all seg.	sung seg.
no separation	51	53	55	38	49	57	64
w/ uncertainty	60	63	53	43	55	57	64
w/ uncertainty	<b>71</b>	<b>72</b>	<b>84</b>	<b>83</b>	<b>77</b>	<b>85</b>	<b>94</b>

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# Summary

Uncertainty handling is a promising approach for the integration of source separation and classification, which almost reaches the performance achieved on clean data when the uncertainty is known.

Principled uncertainty estimation, propagation and decoding techniques do not always work better than heuristic techniques though. Greater understanding of these heuristics is needed.

Perspectives:

- exploitation the uncertainties about other parameters, e.g., the source spatial location,
- understanding the interplay between source separation methods and uncertainty estimators on the classification performance



## Challenges, workshop and resources

2nd CHiME Speech Separation and Recognition Challenge

[http://spandh.dcs.shef.ac.uk/chime\\_challenge/](http://spandh.dcs.shef.ac.uk/chime_challenge/)

Deadline: January 15, 2013

4th Signal Separation Evaluation Campaign (SiSEC)

<http://sisec.wiki.irisa.fr/>

Deadline: Spring 2013, to be announced soon

2nd Int. Workshop on Machine Listening in Multisource Environments

[http://spandh.dcs.shef.ac.uk/chime\\_workshop/](http://spandh.dcs.shef.ac.uk/chime_workshop/)

Vancouver, June 1, 2013 (in conjunction with ICASSP)

Other resources

<http://lvacentral.inria.fr/>

[lvalist@googlegroups.com](mailto:lvalist@googlegroups.com)

[machinelisting@googlegroups.com](mailto:machinelisting@googlegroups.com)

## References

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