# A New Objective Intelligibility Measure For Time-Frequency Weighted Noisy Speech

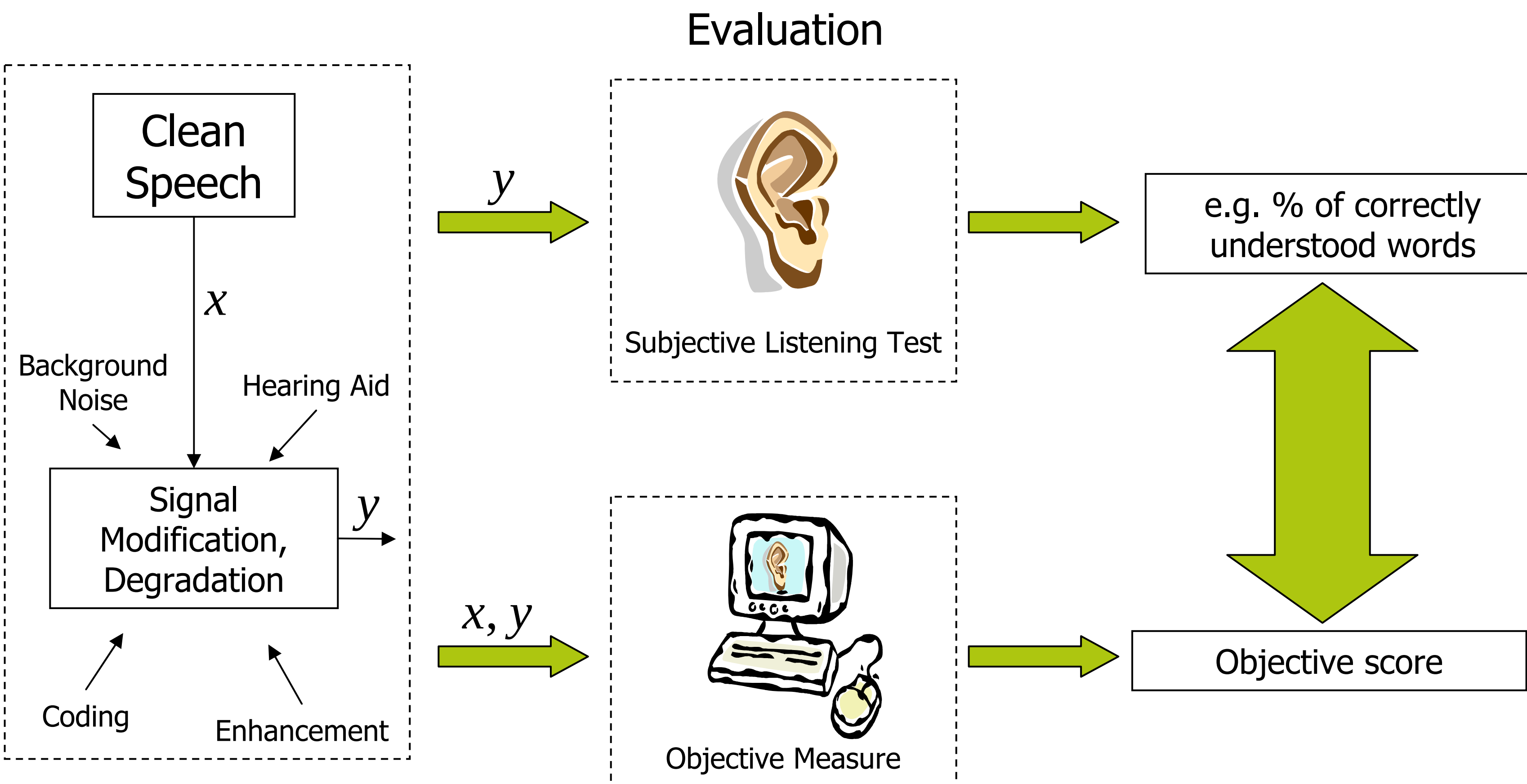
Cees Taal[1], Richard Hendriks[1], Richard Heusdens[1], Jesper Jensen[2]

7-1-2010

[1] Delft University of Technology, Signal Information & Processing Lab, Delft, the Netherlands.

[2] Oticon A/S, Smørum, Copenhagen, Denmark.

# Introduction
## Background



# Introduction
## Motivation

- In this research, the focus is on time-frequency (TF) weighted noisy speech
  - e.g., single-channel noise reduction, speech separation etc.

- Why?
  - Most conventional objective measures are not reliable for this type of processing
  - Such a reliable measure is desired in the field of noise-reduction

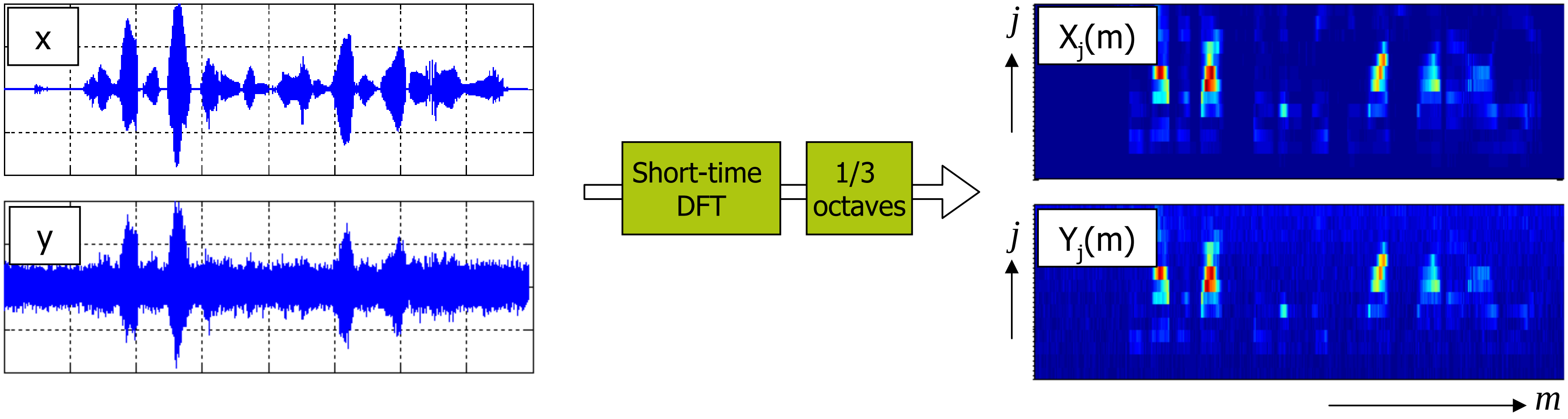
We propose a new objective measure which,

- … shows high correlation with intelligibility of noisy and TF-weighted noisy speech
- … is simple (very few parameters)
- … based on short-time segments (~400 ms)

# Method

- First, TF-decomposition is applied to clean and processed speech
  - 15, 1/3 octave bands, by merging short-time (~25 ms) DFT-bins
  - Bands cover a relevant frequency range for speech intelligibility (~150-4500 Hz)

- Notation:
  - Band index: j, time index: m
  - Clean speech TF-unit: $X_j(m)$, processed speech TF-unit: $Y_j(m)$

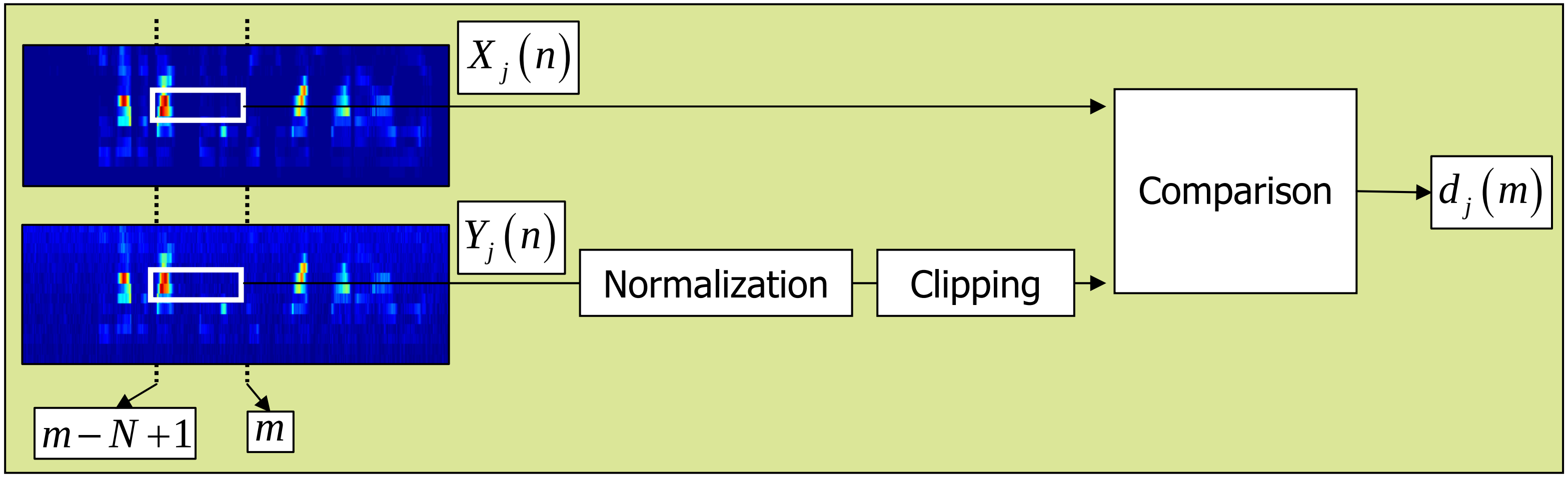


# Method

## Intermediate Intelligibility Measure

- Model depends on intermediate intelligibility measure: $d_j(m)$
  - $d_j(m)$ depends on short segments (~400 ms) of $X_j(n)$ and $Y_j(n)$, per band
  - Where $n \in \{m-N+1, m-N+2, \ldots, m\}$ and N=30

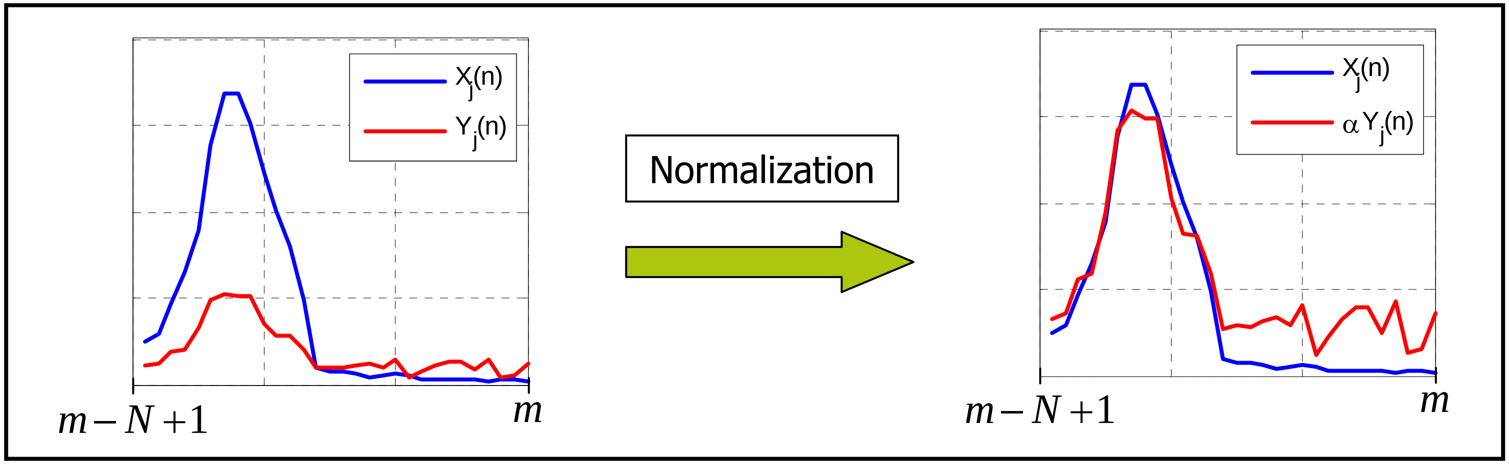
- Before comparison, Yj(n) is first modified as follows:
  - Normalization: Compensate for local energy differences
  - Clipping: To make sure speech is inside range relevant for intelligibility

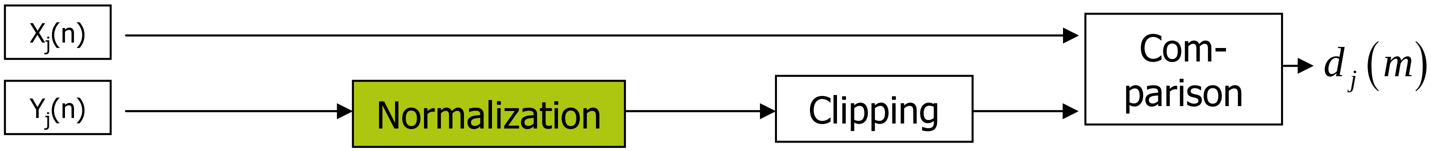


# Method

- $Y_j(n)$ is normalized such that its energy equals the energy of $X_j(n)$:

$$\alpha Y_j(n) = \frac{\sqrt{\sum_n X_j(n)^2}}{\sqrt{\sum_n Y_j(n)^2}} Y_j(n)$$

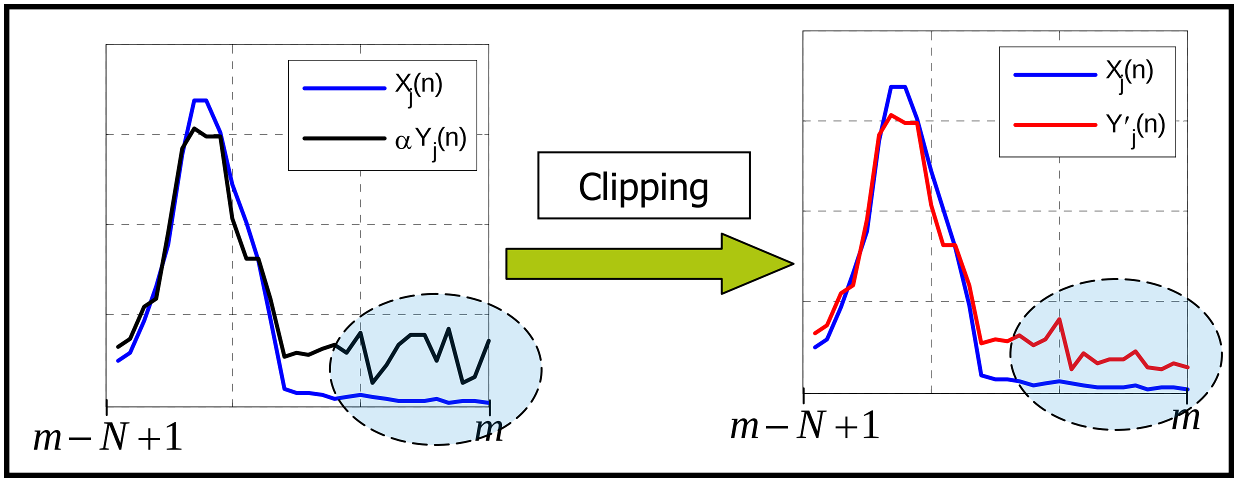


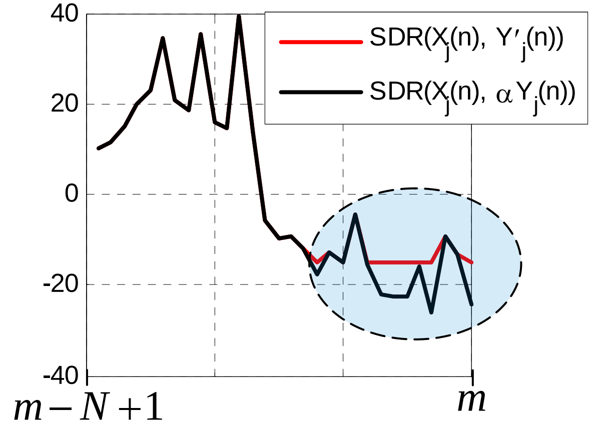



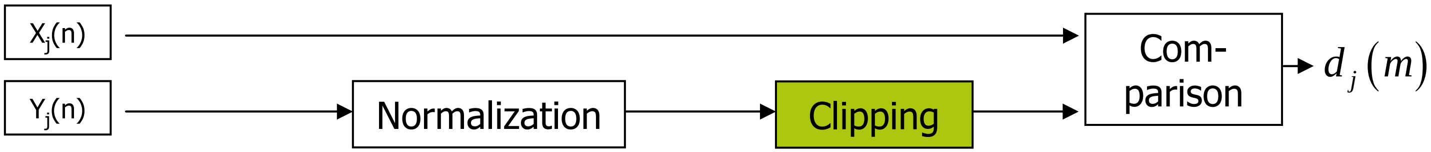
# Method

- $\alpha Y_j(n)$ is clipped to lower-bound the signal to distortion ratio to -15 dB which gives $Y'_j(n)$

$$SDR(A,B) = 10\log_{10}\left(\frac{A^2}{(B-A)^2}\right)$$



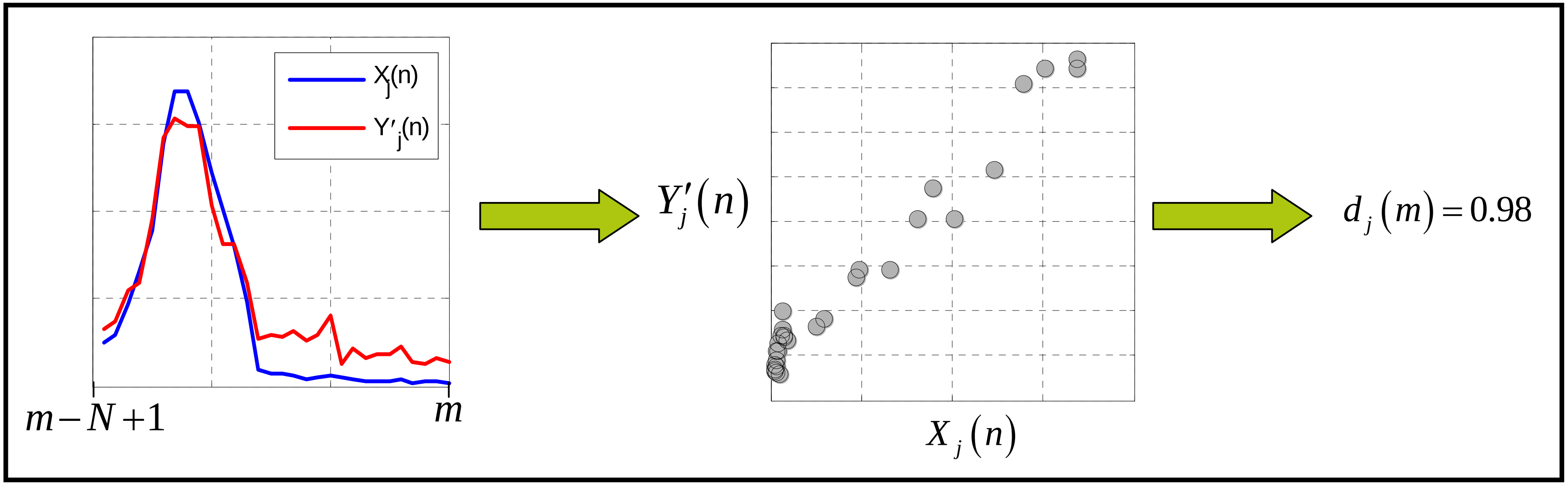



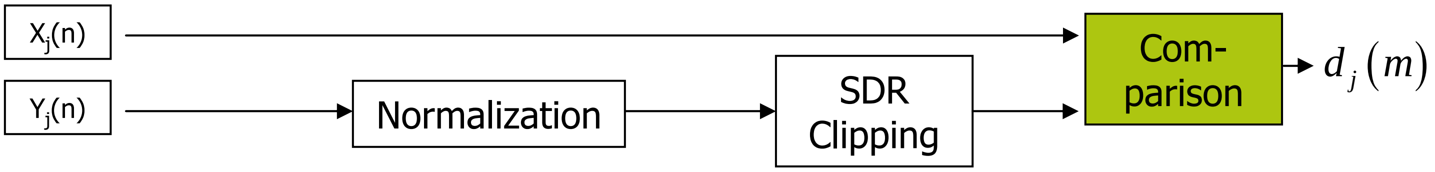



# Method

- $d_j(m)$ equals correlation coefficient between clean and processed speech short-time segments

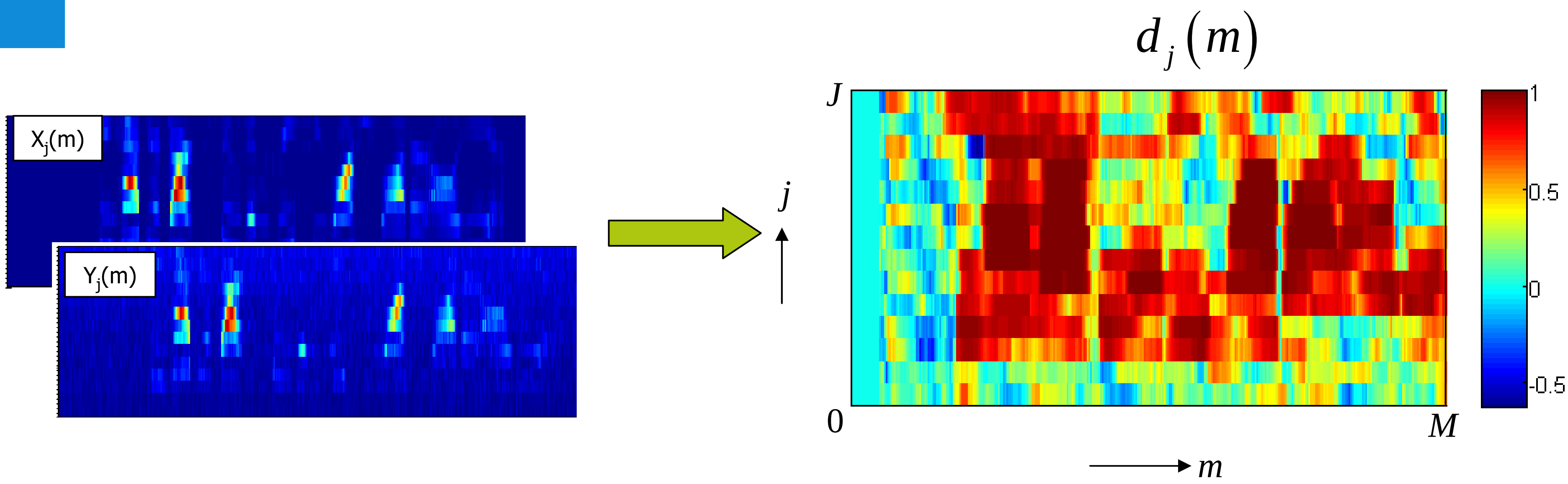
$$d_j(m) = \frac{\sum_n \left(X_j(n) - \mu_X\right)\left(Y_j'(n) - \mu_{Y'}\right)}{\sqrt{\sum_n \left(X_j(n) - \mu_X\right)^2 \sum_n \left(Y_j'(n) - \mu_{Y'}\right)^2}}$$



# Method

## Eventual outcome




- Eventual outcome is defined as the average over all intermediate intelligibility measures:

$$d = \frac{1}{JM} \sum_{m,j} d_j(m)$$

# Subjective Data

- Subjective data origins from Kjems *et al.* (2009)
  - Speech is degraded with additive noise
  - Noisy speech is processed with a technique called 'Ideal Time Frequency Segregation' (ITFS), Brungart *et al.* (2006)

- In total 167 different conditions are evaluated
  - 3 SNRs
  - 4 noise types
  - Various settings of ITFS-algorithm

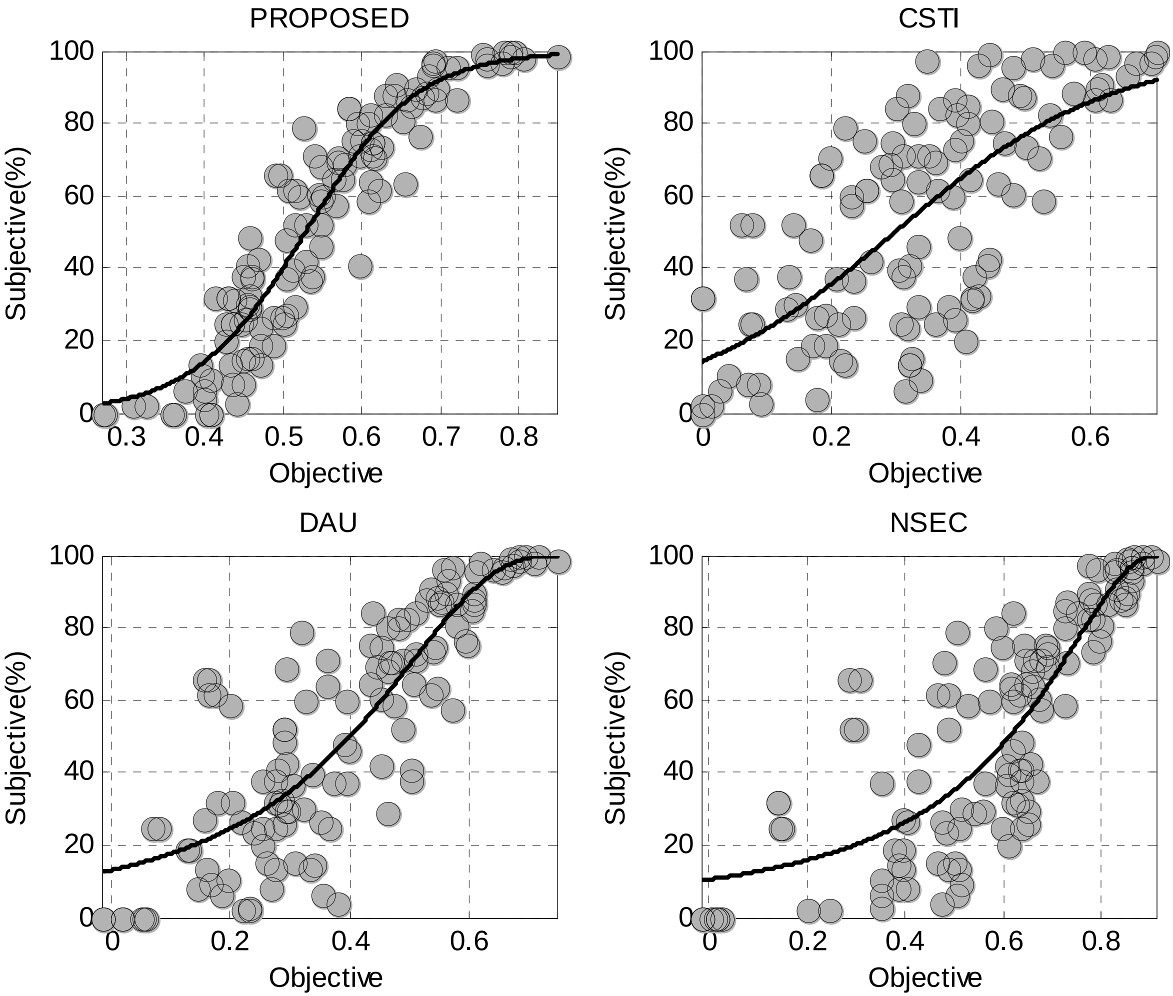
# Experiment

- Proposed method is compared with three reference objective measures:
  - DAU: Dau auditory model (Dau et. al, 1996)
  - NSEC: (Boldt & Ellis, 2009)
  - CSTI: Normalized covariance based STI (Goldsworthy & Greenberg, 2006)
- All these measures are promising candidates for TF-weighted noisy speech

# Results

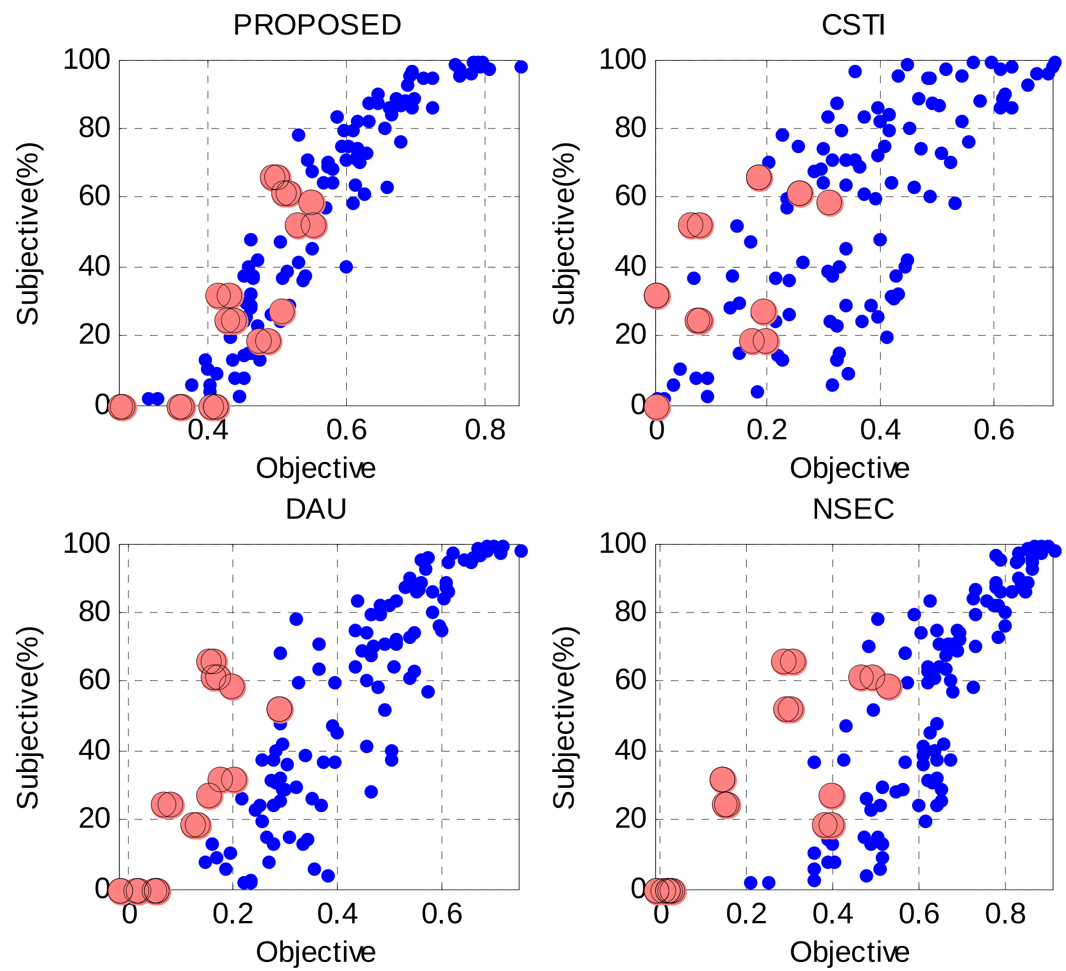
- Figure of merits:
  - RMSE (σ)
  - Correlation Coefficient (ρ)

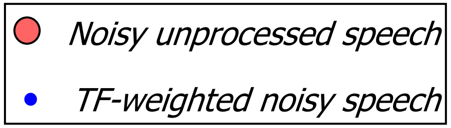
| | PROP | CSTI | DAU | NSEC |
|---|---|---|---|---|
| σ | 10.2% | 21.8% | 16.4% | 17.1% |
| ρ | 0.95 | 0.73 | 0.86 | 0.84 |



# Results

- Reference objective measures underestimate intelligibility of noisy unprocessed speech
- Proposed method good results with both noisy and TF-weighted noisy speech




TU Delft

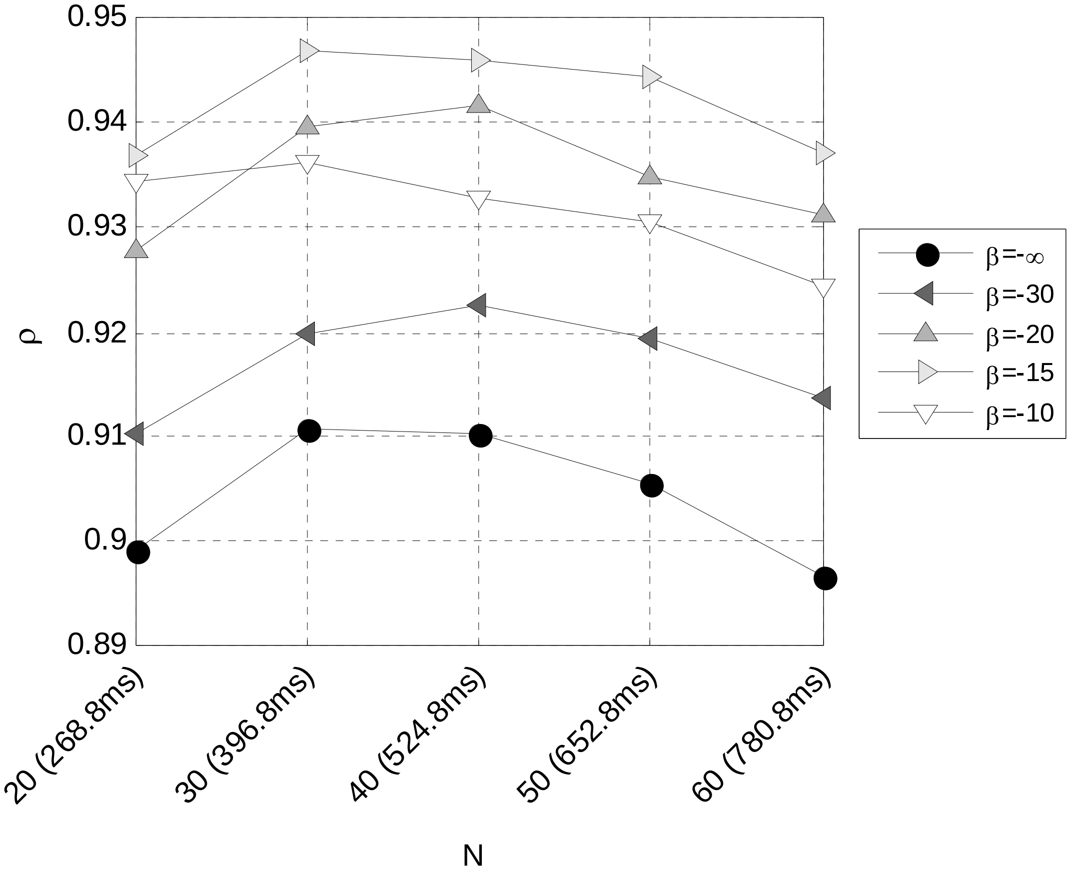
# Conclusions

- A new objective intelligibility measure was presented, based on an intermediate measure for short time-frequency regions (~400 ms)

- The proposed method:
  - …showed high correlation with TF-weighted noisy speech
  - …showed better performance then three other reference objective measures
  - … does not underestimate the intelligibility of the unprocessed noisy speech, which was the case for the three reference objective measures

- Matlab code available: http://www.ceestaal.nl/stoi.zip

# Experimental results

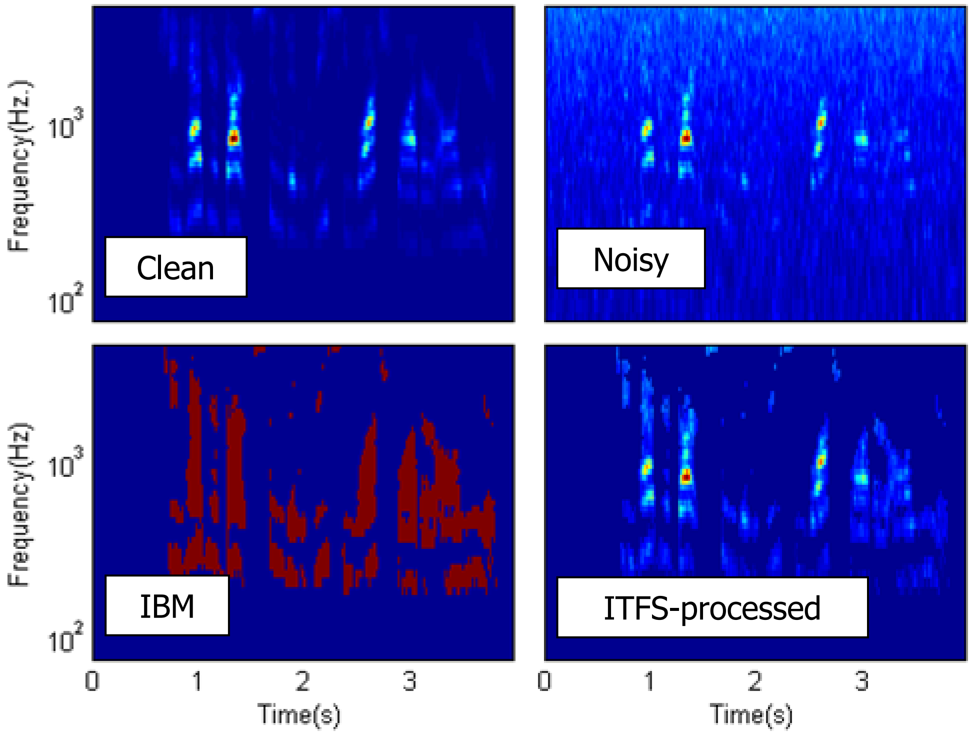


# Subjective Data

## Ideal Time-Frequency Segregation

- Binary time-frequency weighting is applied to noisy speech (Ideal Binary Mask, IBM)
- Mask set to '1' when local SNR within TF-unit exceeds user-defined local criterion (LC):

$$IBM(f,t) = \begin{cases} 1, & \text{if } \dfrac{\text{clean}(f,t)}{\text{noise}(f,t)} > LC \\ 0, & \text{otherwise} \end{cases}$$



# Subjective Data

## Ideal Time-Frequency Segregation

- In total 167 different conditions are evaluated:
  - Speech shaped noise, café noise, car interior noise, noise from bottling factory hall
  - 8 different LC-values
  - 3 SNRs: 20% SRT, 50% SRT, -60 dB