

# Room Acoustics, PA Systems and Speech Intelligibility for Voice Alarm Systems using the example of the Cruise Center Steinwerder

Anselm Goertz - IFAA

Alfred Schmitz - IFAA

**TOA Partner Meeting** September 5<sup>th</sup> 2016 Hamburg  
Cruise Center Steinwerder

## Overview



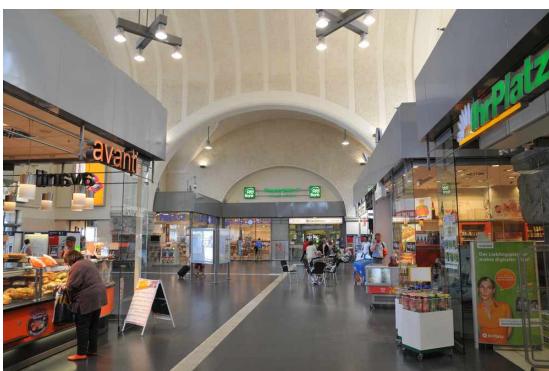
### Room Acoustics and Speech Intelligibility

#### Basics

|  |       |
|--|-------|
| 1. Introduction  | 2-4   |
| 2. STI (Speech Transmission Index) Basics                            | 5-16  |
| 3. Standards   | 17    |
| 4. Design of a PA system   |       |
| 1. Basics about PA systems   | 18    |
| 2. Room Acoustics and Reverberation Time                             | 19-21 |
| 3. Noise Level   | 22    |
| 4. Measurement Equipment for Reverberation Time, Noise Level and STI | 23    |
| 5. Maximum SPL (sound pressure level) and Signal Crest factor        | 24    |

#### Example

|   |       |
|---|-------|
| 5. Cruise Center III in Hamburg Steinwerder | 25-38 |
| 6. Simulations, their Results and Meaning   | 39-41 |
| 7. Measurement Results and Conclusion       | 42    |



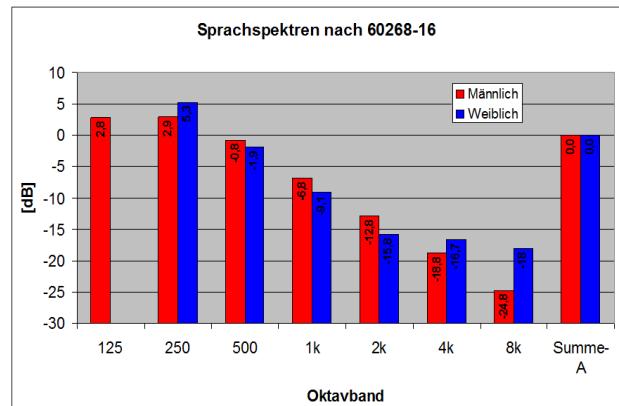
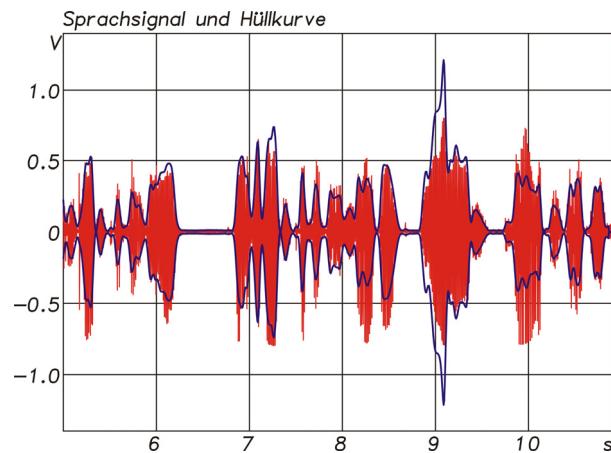
## The PA System

- Only for information and entertainment
- Voice alarm (VA)
- Common minimum target:  
Sufficient speech intelligibility
- Disturbing influences:
  - Noise (Signal/Noise)
  - Reverberation (Room Acoustics)
  - Insufficient level (Hearing threshold)
  - Too high levels (Masking effect)



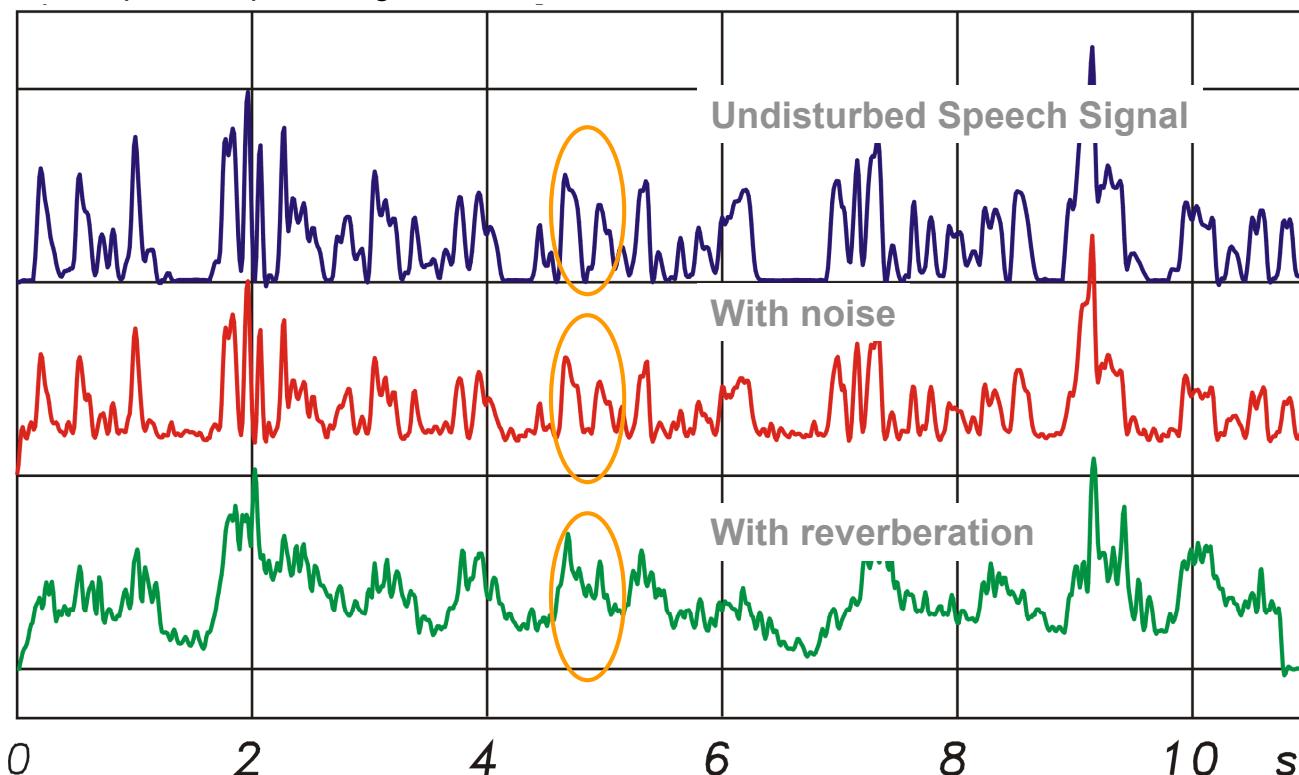
## ■ Speech is a modulated Signal

- ⇒ The information content is transported by the modulation
- ⇒ Reverberation, noise and band limiting lead to a loss of modulation in the signal and thus to a loss of information, that means it causes reduced speech intelligibility
- ⇒ Modulation frequencies up to 20 Hz
- ⇒ Spectral content in 7 octave bands from 125 Hz to 8 kHz



## Modulation loss by reverberation and noise

Envelope of a speech signal



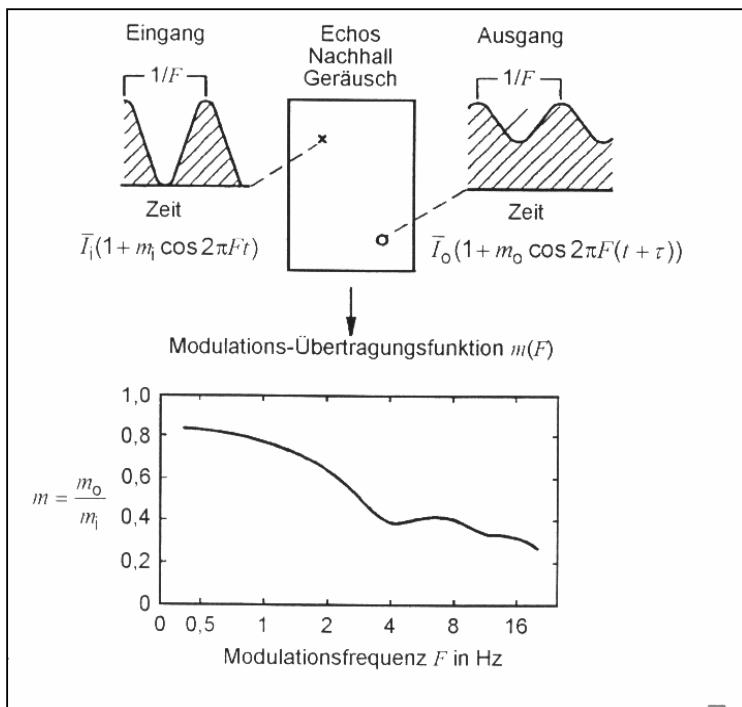
- Ambient noise is usually highly volatile concerning both time and spectral composition. Therefore it is difficult to define.
- Mostly only rough approximation: ... up to 65, 75, 85, ... dBA
- The decisive factor is not the noise considered alone, ...
- ... but rather the ratio between the signal level and the noise level
- Solution: sufficiently loud voice reproduction, but ...
  - Starting with a level of approximate 80 dBA the speech intelligibility goes down caused by the masking effect
  - Variable noise levels require an automatic ambient noise control and level adaptation
  - the cost of the sound system should remain reasonable for example:  
PA system at Cologne main station with 3 kW power for each platform

## Challenge No.2 Reverberation

- Reverberation occurs in big halls with mostly reverberant surfaces (glass, concrete, stoneware, metal, ...)
- for 1,5 s and longer reverberation times special sound system concepts are required (highly directional radiation to the audience)
- The key is to transmit as much as possible direct sound from the speakers to the audience and to excite the reverberation as little as possible
- Solutions:
  - a few highly directional speakers  
(good approach for big halls like churches, departure and arrival halls....)
  - many small speakers close to the audience  
(good approach for subareas in big halls like platforms in railway stations)
  - Room acoustic optimizations are the best way, but not possible in most cases

- Long reverberation ( **>1,5 s** )
  - High requirements for the speakers directivity
    - Churches and mosques 2 – 10 s
    - Road tunnels 10 – 30 s
    - Sport stadiums 2 – 6 s
    - Railway stations, airport lobbies 2 - 5 s
  
- Loud environment with high noise levels ( **>70 dBA** )
  - High requirements on the maximum SPL (sound pressure level)
    - Railway stations 85 dBA  $\Rightarrow$  signal level for speech min. 95 dBA
    - Sport stadiums 95 dBA  $\Rightarrow$  signal level for speech min. 105 dBA
  
- Additional requirements on voice alarm systems (**VA**):
  - Minimum values for speech intelligibility for standard- and error mode according to VA standards
  - Monitoring of the system, reliability, ....
  - All components certified according to standard **EN54**... (EN54-4, EN54-16, EN54-24)

## Modulation Transfer Function (MTF)



**Objective rating of the speech intelligibility by the STI measurement (Speech Transmission Index)**

**The STI is calculated from the loss of modulation at 98 coefficients for different modulation frequencies from 0,63 Hz to 12,5 Hz and for the octave bands from 125 Hz to 8 kHz.**

**This takes into consideration:**

- reverberation
- Signal to Noise
- Hearing Threshold
- Masking effects
- Various other effects ...

**STI range from 0 to 1**

| Measured STI | Qualification category |
|--------------|------------------------|
| 0...0,3      | bad                    |
| 0,3..0,45    | poor                   |
| 0,45..0,6    | fair                   |
| 0,6..0,75    | good                   |
| 0,75..1      | excellent              |

- **Minimum requirements:**

- For voice alarm systems: 0,5 considering the masking effect

- **Exceptions:**

- For a fixed group of people: 0,45 (example: factory side)
- In case of a system error: 0,45 for a single error  
(only the STI criteria is relevant, the -3 dB criteria is no longer valid) VDE 0833-4 2014
- For critical acoustic environment (long reverberation, high noise level): 0,45

## STI requirements from EN 60268-16 standard 2011

### Examples of STI qualification bands and typical applications

The information in the Table G.1 is presented as an example of usage.

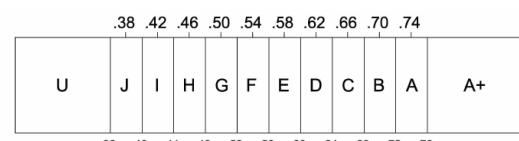
Table G.1 – Examples between STI qualification bands and typical applications

| Category | Nominal STI value | Type of message information        | Examples of typical uses (for natural or reproduced voice)                       | Comment  |
|----------|-------------------|------------------------------------|--|--|
| A+       | >0,76             |                                    | Recording studios  | Excellent intelligibility but rarely achievable in most environments |
| A        | 0,74              | Complex messages, unfamiliar words | Theatres, speech auditoria, parliaments, courts, Assistive Hearing Systems (AHS) | High speech intelligibility  |
| B        | 0,7               | Complex messages, unfamiliar words | Theatres, speech auditoria, teleconferencing, parliaments, courts                | High speech intelligibility  |
| C        | 0,66              | Complex messages, unfamiliar words | Lecture theatres, classrooms, concert halls                                      | Good speech intelligibility  |
| D        | 0,62              | Complex messages, familiar words   | Concert halls, modern churches   | High quality PA systems  |
| E        | 0,58              | Complex messages, familiar context | PA systems in shopping malls, public buildings offices, VA systems, cathedrals   | Good quality PA systems  |
| F        | 0,54              | Complex messages, familiar context | Shopping malls, public buildings offices, VA systems                             | Target value for VA systems  |
| G        | 0,5               | Complex messages, familiar context | VA and PA systems in difficult acoustic environments                             | Normal lower limit for VA systems                                    |
| H        | 0,46              | Simple messages, familiar words    | VA and PA systems in very difficult spaces                                       |  |
| I        | 0,42              | Simple messages, familiar context  | Not suitable for PA systems  |  |
| J        | 0,38              |                                    | Not suitable for PA systems  |  |
| U        | <0,36             |                                    | Not suitable for PA systems  |  |

NOTE 1 These values should be regarded as minimum target values.

NOTE 2 Perceived intelligibility relating to each category will also depend on the frequency response at each listening position.

NOTE 3 The STI values refer to measured values in sample listening positions or as required by specific application standards.



- STI qualification bands and typical applications (by Peter Mapp)
- All nominal STI values calculated as average value minus standard deviation
- Table only in the informative part of the standard only for orientation!

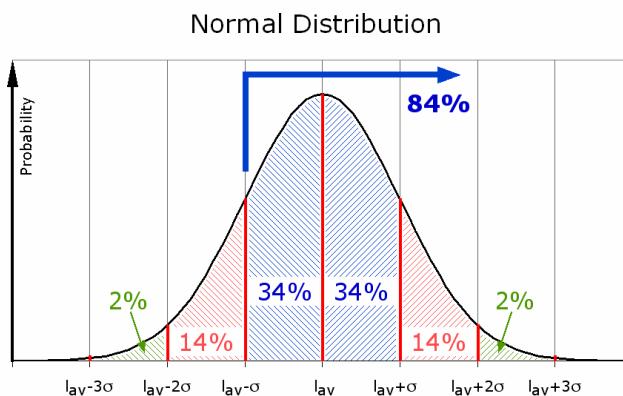
- arithmetic average – standard deviation  $\geq 0,5$

$$I_{av} - \sigma \geq 0,5$$

$$I_{av} = \frac{1}{n}(a_1 + a_2 + \dots + a_n)$$

$$\sigma = \sqrt{\frac{n \cdot \sum_{i=1}^n a_i^2 - \left(\sum_{i=1}^n a_i\right)^2}{n(n-1)}}$$

- Measurement point grid: 6 m (recommendation only)



## Relationship between STI and word and sentences scores

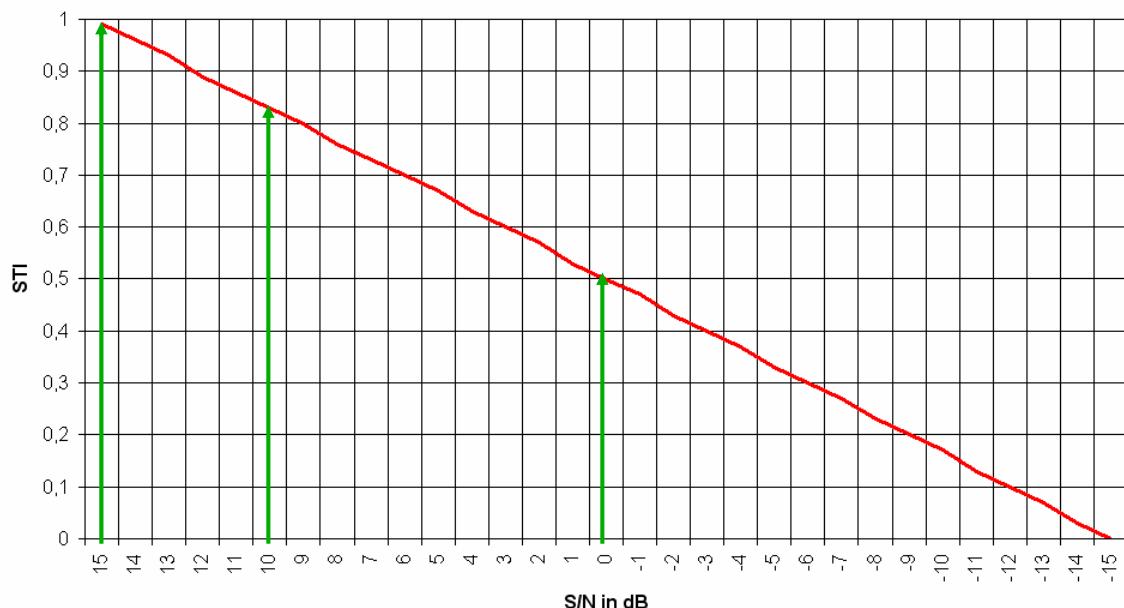
| STI-value  | CIS-value   | Alcons in % | qualification EN 60268 | Syllables score in % | Word score in % | Sentences score in % |
|------------|-------------|-------------|------------------------|----------------------|-----------------|----------------------|
| 0...0,3    | 0...0,48    | 100...36    | Bad                    | 0...32               | 0...37          | 0...75               |
| 0,3...0,45 | 0,48...0,65 | 36...17     | Poor                   | 32...61              | 37...68         | 75...93              |
| 0,45...0,6 | 0,65...0,78 | 17...8      | Fair                   | 61...85              | 68...88         | 93...98              |
| 0,6...0,75 | 0,78...0,87 | 8...3,6     | Good                   | 85...98              | 88...98         | 98...100             |
| 0,75...1   | 0,87...1    | 3,6...1     | Excellent              | 98...100             | 98...100        | 100                  |

Farrell-Becker-Equation:

$$CIS = 1 + \log(STI)$$

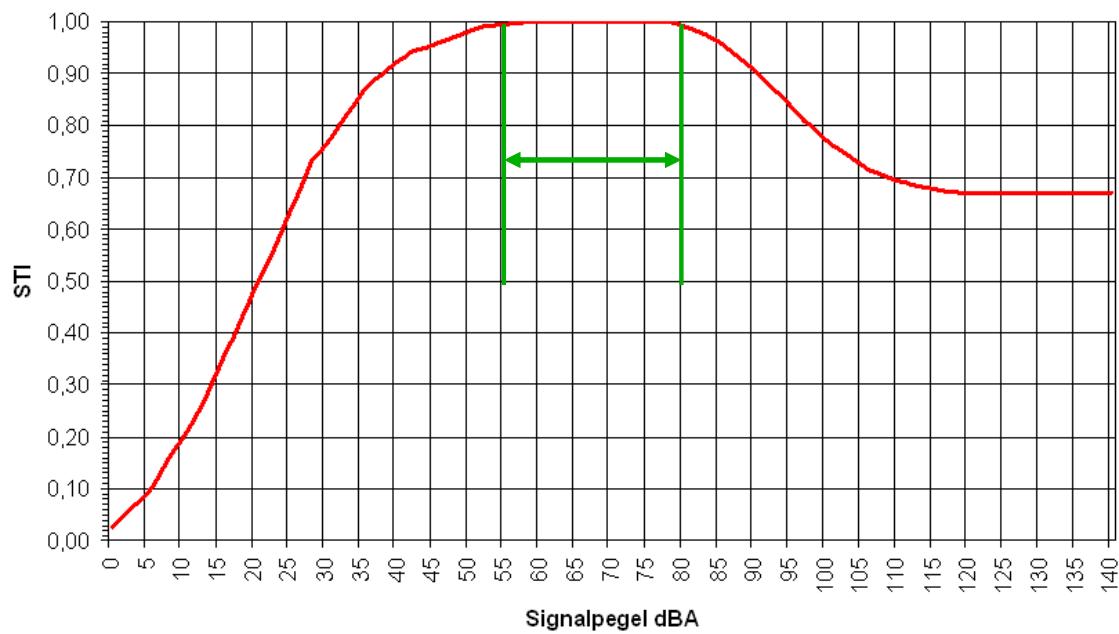
$$ALCons = 10^{\frac{1-STI}{0,45}}$$

## STI depending on the S/N at 65 dBA signal level



## STI depending on the masking and hearing threshold

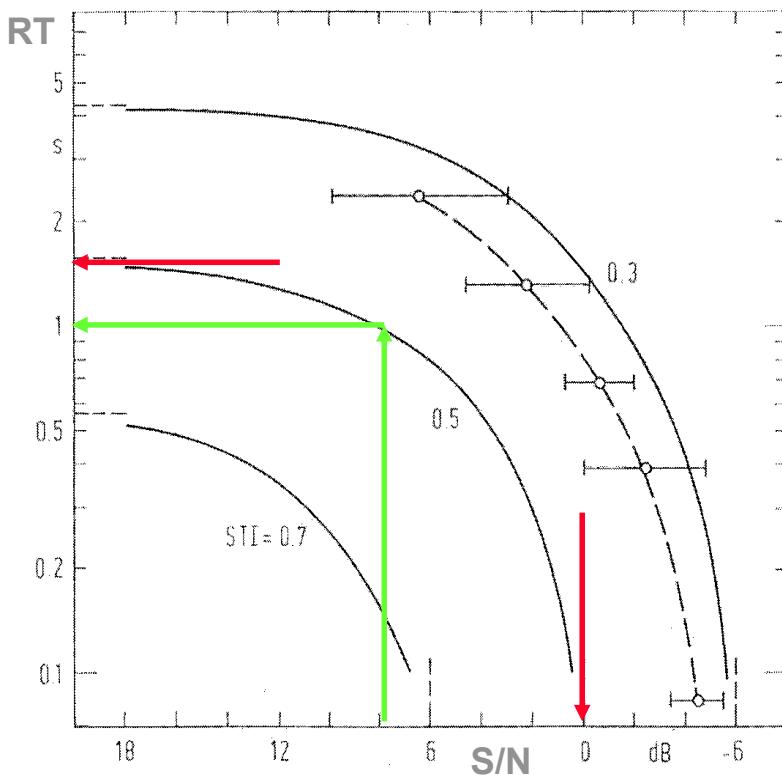
### STI depending on the signal level



- IEC 60268-16 ; 2011  
Sound System Equipment  
Objective rating of speech intelligibility by the speech transmission index
- DIN EN 60849 ; 1999  
Sound Systems for Emergency Purpose
- DIN EN 50849 ; expected 2016  
Sound Systems for Emergency Purpose, which are not Part of Fire Detection Systems
- DIN VDE 0833-4 national application standard  
largely corresponds to the standard EN TS 54-32 ; 2016  
guidelines for the planning, design, installation, commissioning, use, maintenance and modification of voice alarm systems
- EN 54-xx requirements for all parts of fire alarm systems  
Part 4: Power supply equipment  
Part 16: Voice alarm control and indicating equipment  
Part 24: Components of voice alarm systems - Loudspeakers

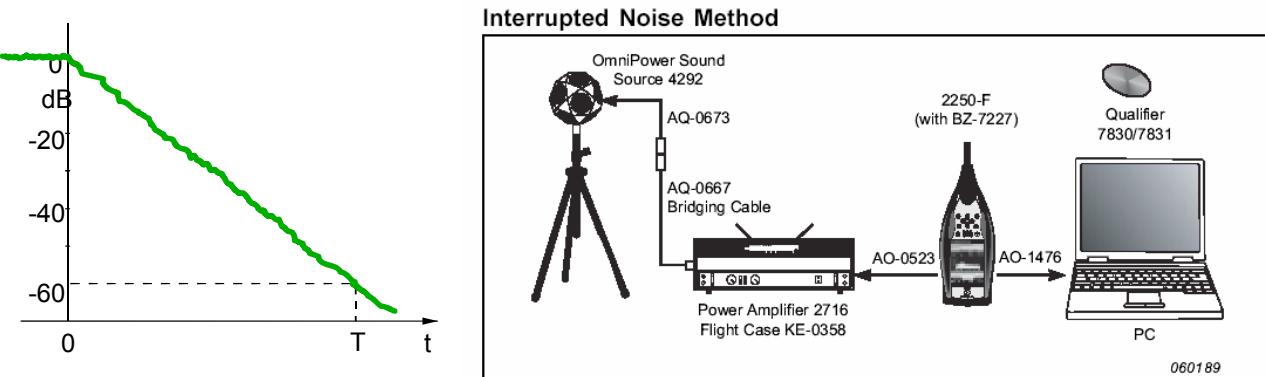
## How to design a PA system ?

- Starting position:
  - Reverberation time in octave or 1/3 octave band (average values only for orientation)
  - Noise level in octave or 1/3 octave band (A-weighted total SPL only for orientation)
    - Timing of the noise level
  - Important standards
    - 60849 or 50849 for voice alarm systems
  - Further conditions
    - Conservation of historical buildings
    - Later modifications to the building
    - Disturbances of the environment
  - More questions
    - Which speaker positions are possible?
    - Are active speaker systems, like DSP controlled line sources, possible ?
    - Is the power supply and emergency supply sufficient ?

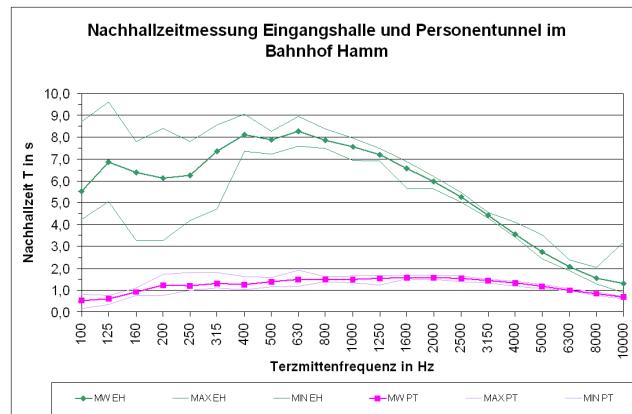


- Graphs for non directional sources like:
  - Small ceiling speakers
  - Simple fullrange systems
- For reverberation times of 1 s and more room acoustic improvements or highly directional speakers are required

## Measurement of the Reverberation Time



# Example Reverberation Time Measurement



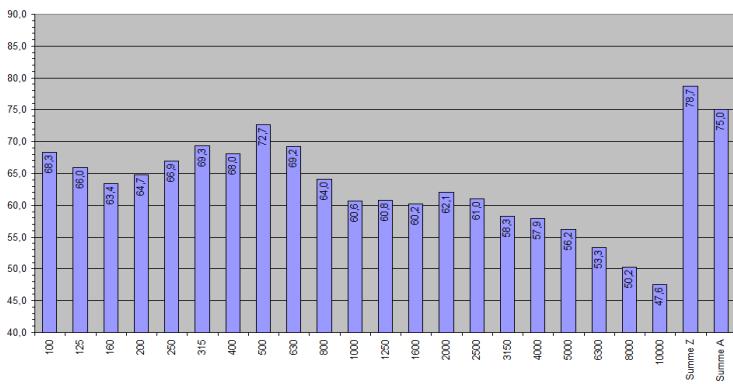
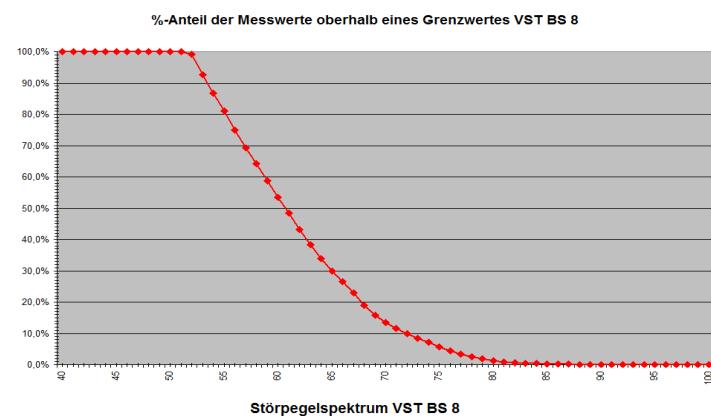
- Lobby of a railway station with very long reverberation times up to 8 s

- Installation with two 5m long DSP controlled line sources (STI very close above 0,5)

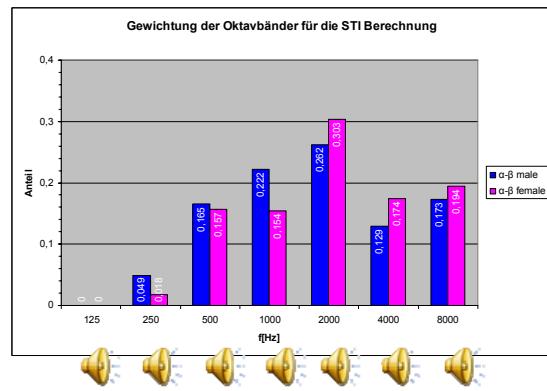
- Platform entrance with reverberation times of approximate 1,5 s

- Installation with distributed line sources with small full range speakers (STI very close above 0,5)

# Example Noise Level Measurement



- Long time sampling for  $L_{eq}$  values of defined time periods  $dt$
- Statistical evaluation
- Spectral analysis of the noise
- Relation to the signal spectrum calculated as  $L_{eq}$  values for octave bands from 125 Hz to 8k



- Noise Measurements (long-term recordings)
- Reverberation Time (with noise or with impulse source)
- STI measurement and analysis
- Impedance measurements and speaker tests



## Crest factor, the critical point ?

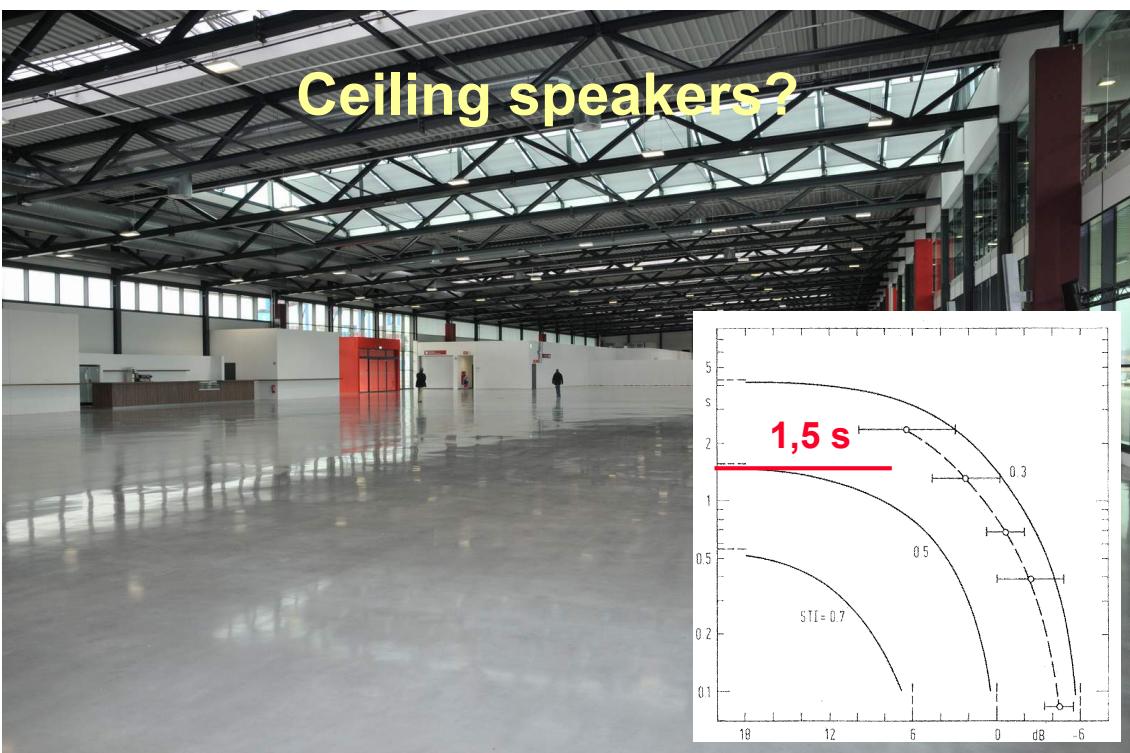
- Simulations are calculated with average power values of the speakers  
(2h average power according to AES)
- On the acoustical side, there is the  $L_{eq}$  SPL value  
(equivalent to the total Sound Energy over a given period of time)
- Example TOA SR-4S (100V/60W)  
average sensitivity of 94 dB 1W/1m  
calculated SPL for 60 W is approximate 112 dB at 1 m
- The question is:  
How to reach an average power of 60 W with a typical test signal like the STI-PA noise? That is not possible!
- Crest factor (CF):  
Relation of the signal peak level to the RMS value  
(RMS = root mean square)
- Crest factor examples:
  - Sinus signal: 3 dB
  - Speech: 12 - 20 dB
  - STIPA Test signal: 12 - 14 dB
  - Music: 9 - 20 dB
  - Rectangle: 0 dB
- Example SR-4S 100 V
  - amplifier 141 V<sub>pk</sub> max. and 100 V<sub>RMS</sub>
  - CF 3 dB: LS power 60 W<sub>avg.</sub>
  - CF 12 dB: LS power 7,5 W<sub>avg.</sub>
  - Level loss for the  $L_{eq}$  of 9 dB compared to the 60 W calculated value of 112 dB



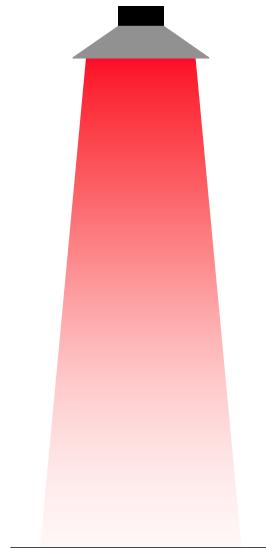
TOA Partner Meeting Sept. 5<sup>th</sup> 2016 Hamburg  
Room Acoustics, PA Systems and Speech Intelligibility for Voice Alarm Systems by Anselm Goertz

V2016\_2  
Folie 25

## Departure Hall



- Colour intensity = level
- Contrast to the environment = modulation = speech intelligibility



# Many small speakers in an reverberant environment

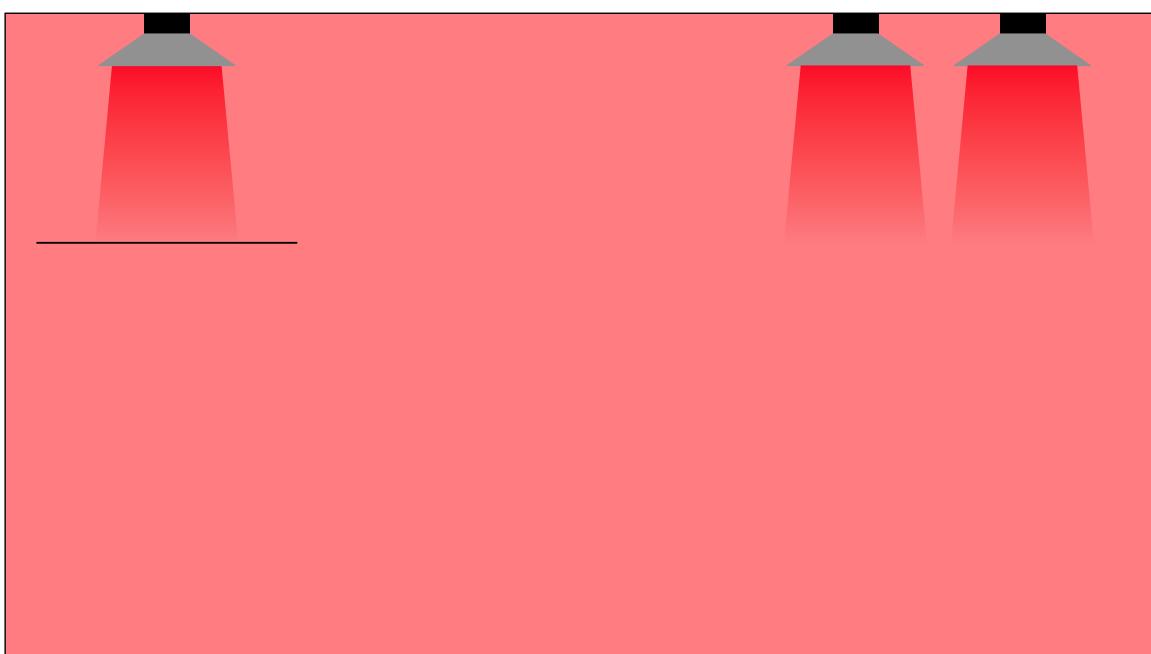
- Colour intensity = level
- Contrast to the environment = modulation = speech intelligibility



- Colour intensity = level
- Contrast to the environment = modulation = speech intelligibility



- Colour intensity = level
- Contrast to the environment = modulation = speech intelligibility



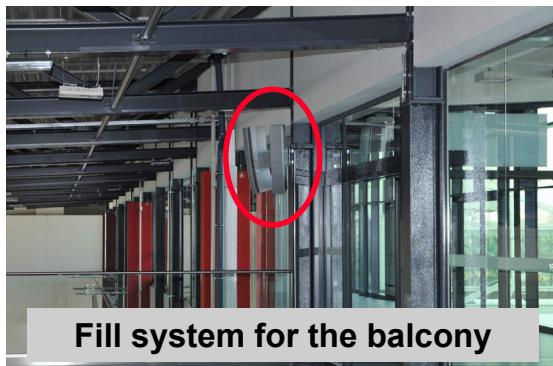
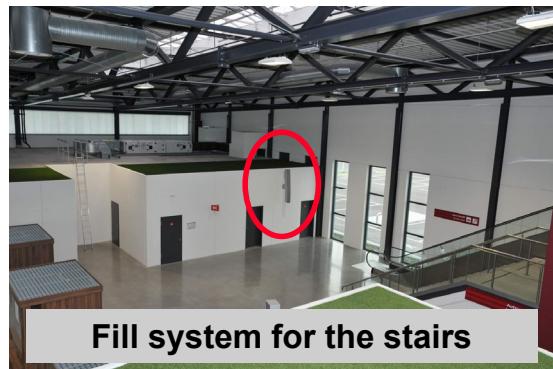
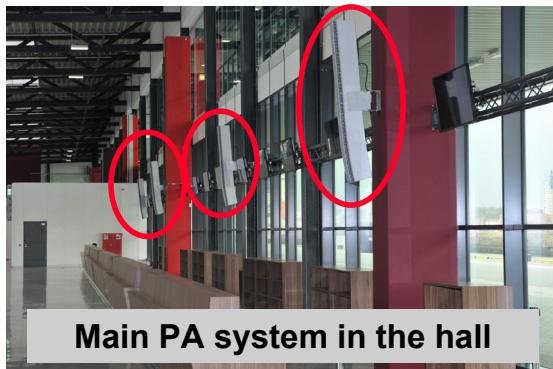
- Colour intensity = level
- Contrast to the environment = modulation = speech intelligibility



## Selection of the loudspeakers

- Target:
  - highly directional sound radiation to the audience
  - As little as possible radiation into the remaining space
  - All listeners are on the ground level
    - Line source speakers
      - horizontal wide coverage
      - and vertical narrow coverage
    - Active DSP controlled line sources ?
      - Power supply ?
      - Emergency power supply ?
      - EN54 components ?
    - Curved passive line source speakers
      - TOA SR-S4
      - Stairs and Skywalk separately considered





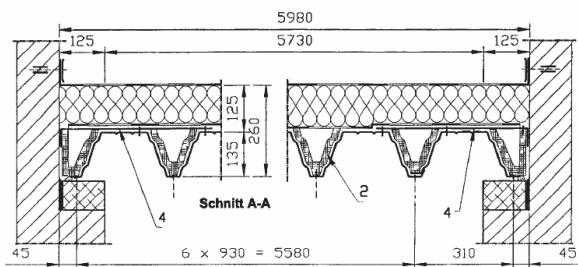
TOA Partner Meeting Sept. 5<sup>th</sup> 2016 Hamburg  
Room Acoustics, PA Systems and Speech Intelligibility for Voice Alarm Systems by Anselm Goertz

V2016\_2  
Folie 33

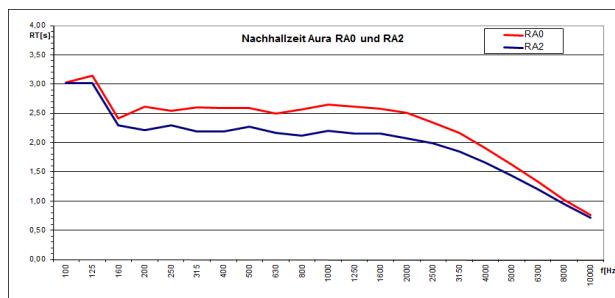
## Room acoustic improvements



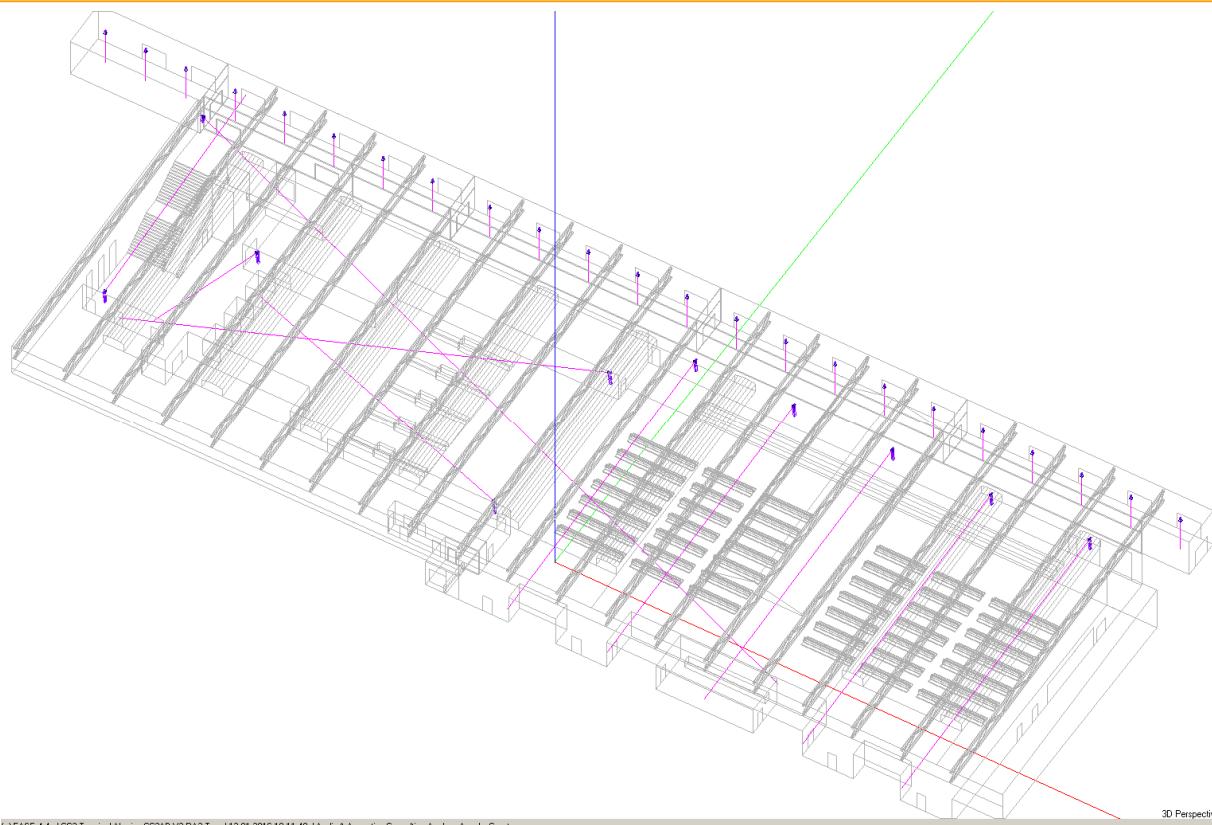
Departure hall with appr. 4.100 m<sup>2</sup>  
perforated trapeze sheet at the ceiling



Additional acoustically absorbing  
perforated walls with appr. 600 m<sup>2</sup>



# Simulation model in EASE with loudspeakers



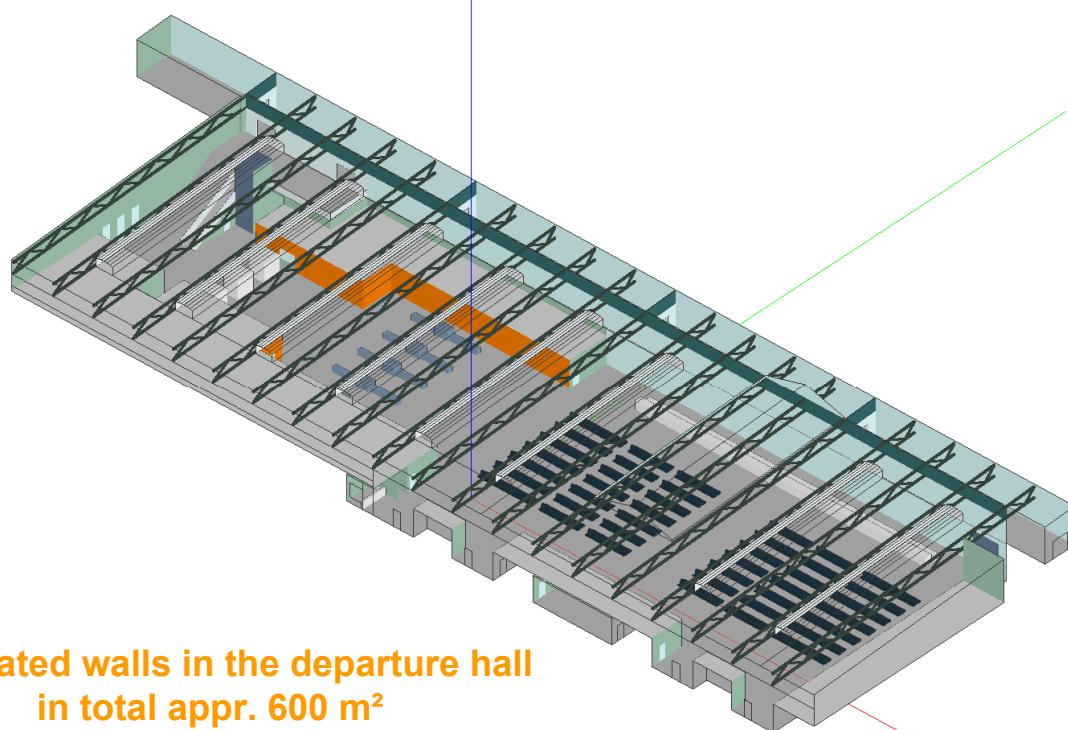
[c] EASE 4.4 / CC3-TerminalAbreise CC3AB/V2/RA2-Toa / 13.01.2016 10:11:40 / Audio & Acoustics Consulting Aachen Anselm Goertz

V2016\_2  
Folie 35

# Simulation model in EASE



Ver: 36° Hor: 138°  
Project: CC3AB/V2/RA2-Basic  
Dye: Makita Colors  
Freq: 1000 Hz



**Perforated walls in the departure hall  
in total appr. 600 m<sup>2</sup>**

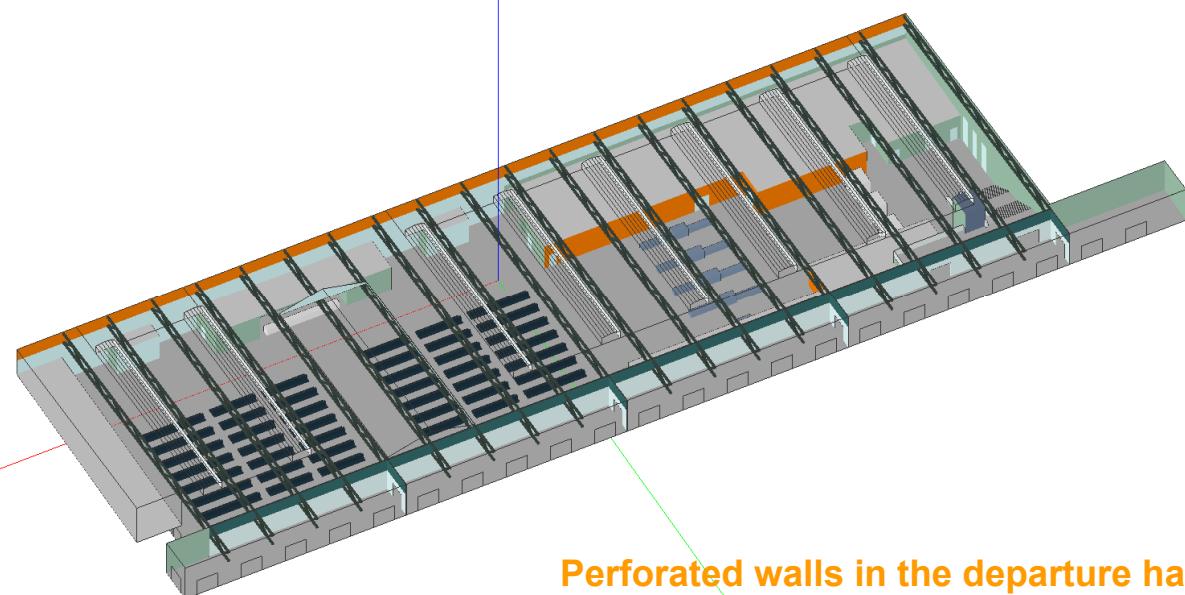
[c] EASE 4.4 / CC3-TerminalAbreise CC3AB/V2/RA2-Basic / 22.08.2014 11:53:30 / Audio & Acoustics Consulting Aachen Anselm Goertz

V2016\_2  
Folie 36

TOA Partner Meeting Sept. 5<sup>th</sup> 2016 Hamburg  
Room Acoustics, PA Systems and Speech Intelligibility for Voice Alarm Systems by Anselm Goertz

# Simulation model in EASE

Ver.-47° Hor.-20°  
Project: CC3AB/V2/RA2-Basic  
Dye: Material Colors  
Freq: 1000 Hz



**Perforated walls in the departure hall  
in total appr. 600 m<sup>2</sup>**

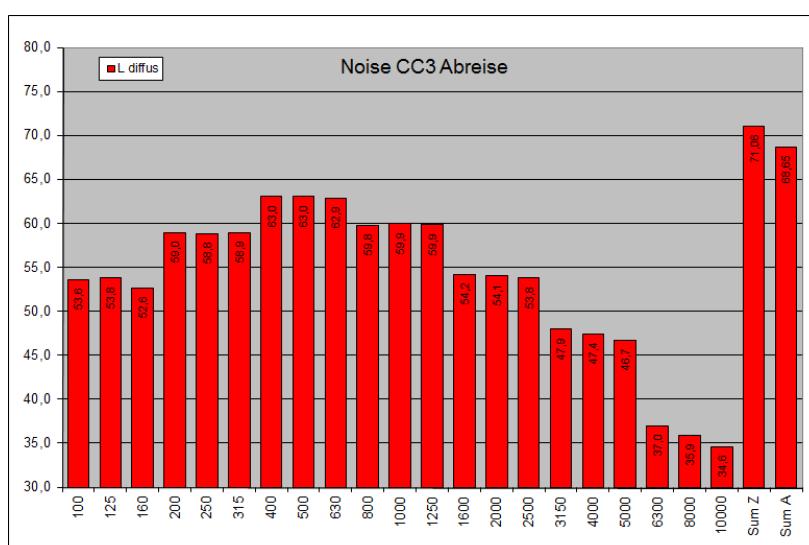
(c) EASE 4.4 / CC3 Terminal Abreise CC3AB-V2-RA2-Basic / 22.08.2014 11:54:13 / Audio & Acoustics Consulting Aachen Anselm Goertz

TOA Partner Meeting Sept. 5<sup>th</sup> 2016 Hamburg  
Room Acoustics, PA Systems and Speech Intelligibility for Voice Alarm Systems by Anselm Goertz

V2016\_2  
Folie 37

## Noise level approximation

- 500 persons talking with normal level  $L_w = 70 \text{ dBA} + 10 \cdot \log(500) = 97 \text{ dBA}$
- Sound power level per person  $L_{WAeq} = 70 \text{ dB}$  (corresponds to appr. 65 dBA DSPL)
- Volume of the room appr.  $43.500 \text{ m}^3$
- Average reverberation time appr. 2,5 s  $L = L_w - 10 \cdot 1g\left(\frac{V/m^3}{T/s}\right) + 13,88 \text{ dB}$



**Noise level:**  
**71,1 dBZ**  
**68,6 dBA**

# Direct SPL only. Mapping and Distribution



CC3-Terminal-Abreise  
Used:  
Lspk: H01 SR-S4(25), H02 SR-S4(25), H03 SR-S4(25), H04 SR-S4(25), H05 SR-S4(25), K01 SR-S4(25), K02 SR-S4(25), Z01 SR-S4(25), Z02 SR-S4(25), G01 SR-S4(5), VG01 F-1000, VG02 F-1000, VG03 F-1005, VG03 F-1004, VG03 F-1003, VG03 F-1002, VG03 F-1001, VG04 F-1000, VG05 F-1000, VG06 F-1000  
Map: Direct SPL [Z]  
Freq: 4000 Hz  
(3/1 Octaves Sum)  
Energy: 2<sup>nd</sup> Octal  
(1/3rd Octave)



(c) EASE 4.4 / CC3-Terminal-Abreise CC3AB-V2-Ra2-Toe-PNK / 13.01.2016 10:57:07 / Audio & Acoustics Consulting Aachen Anselm Goertz

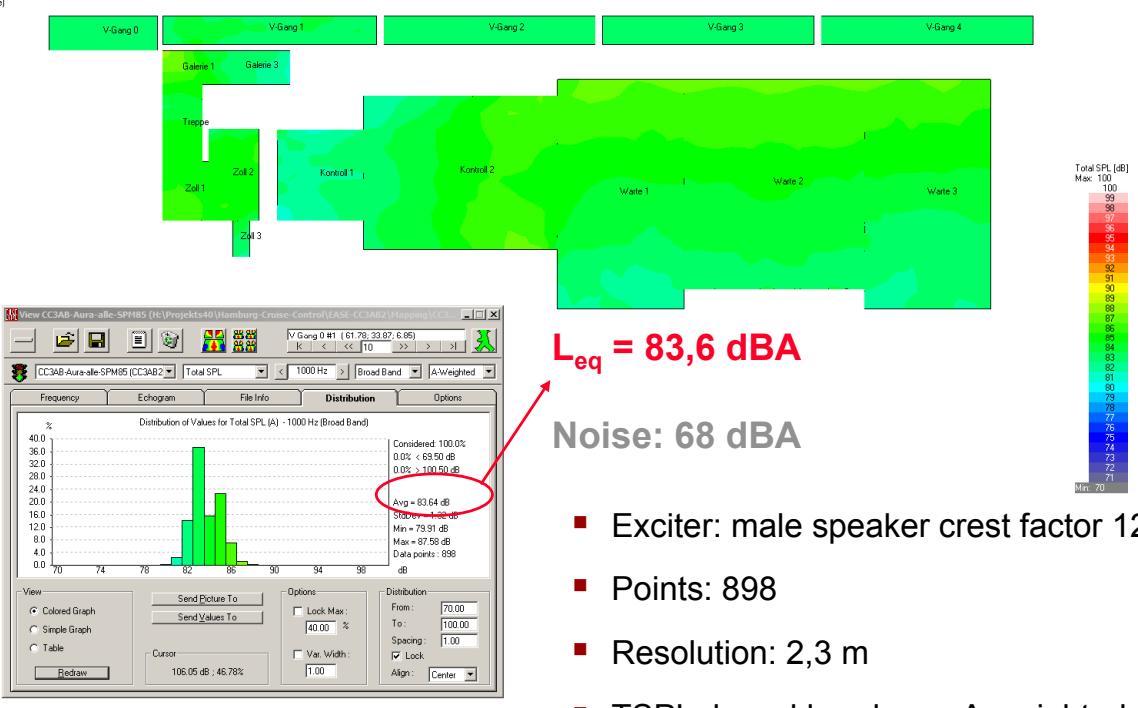
TOA Partner Meeting Sept. 5<sup>th</sup> 2016 Hamburg  
Room Acoustics, PA Systems and Speech Intelligibility for Voice Alarm Systems by Anselm Goertz

V2016\_2  
Folie 39

# Total SPL mapping and distribution



CC3-Terminal-Abreise  
Used:  
Lspk: H01 SR-S4(25), H02 SR-S4(25), H03 SR-S4(25), H04 SR-S4(25), H05 SR-S4(25), K01 SR-S4(25), K02 SR-S4(25), Z01 SR-S4(25), Z02 SR-S4(25), G01 SR-S4(5), VG01 F-1000, VG02 F-1000, VG03 F-1005, VG03 F-1004, VG03 F-1003, VG03 F-1002, VG03 F-1001, VG04 F-1000, VG05 F-1000, VG06 F-1000  
Map: Total SPL (A)  
Freq: 1000 Hz  
(Broad Band Sum)  
Energy: 2<sup>nd</sup> Octal  
(1/3rd Octave)



(c) EASE 4.4 / CC3-Terminal-Abreise CC3AB-V2-Ra2-Toe / 13.01.2016 10:26:32 / Audio & Acoustics Consulting Aachen Anselm Goertz

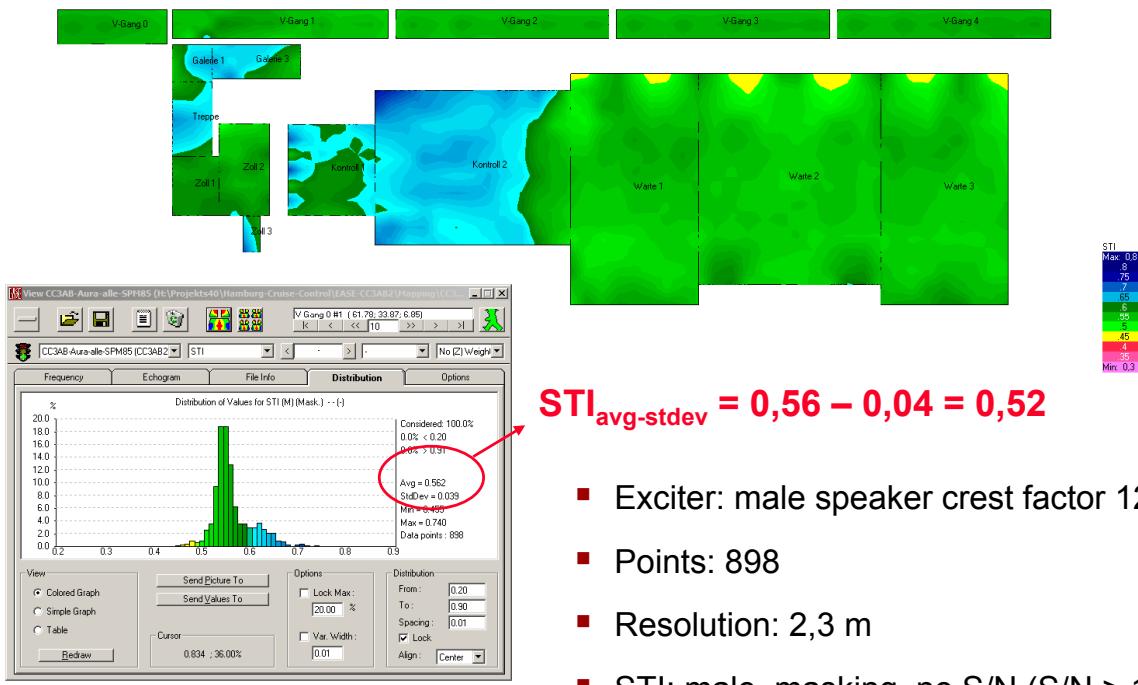
TOA Partner Meeting Sept. 5<sup>th</sup> 2016 Hamburg  
Room Acoustics, PA Systems and Speech Intelligibility for Voice Alarm Systems by Anselm Goertz

V2016\_2  
Folie 40

# Speech intelligibility (STI) mapping and distribution



CC3-TerminalAbreise  
Used:  
Lspk: H01 SR-S4(2S), H02 SR-S4(2S), H03 SR-S4(2S), H04 SR-S4(2S), H05 SR-S4(2S), K01 SR-S4(2S), K02 SR-S4(2S), Z01 SR-S4(2S), Z02 SR-S4(2S), G01 SR-S4(2S), VG01 F-1000, VG02 F-1000, VG03 F-1005, VG03 F-1004, VG03 F-1003, VG03 F-1002, VG03 F-1001, VG04 F-1000, VG05 F-1000, VG06 F-1000  
Map: STI [M] (Mask.)  
Energy: [1/3rd Octave]



(c) EASE 4.4 / CC3-TerminalAbreise CC3AB-V2-Ra2-Toa / 13.01.2016 10:21:54 / Audio & Acoustics Consulting Aachen Anselm Goertz

TOA Partner Meeting Sept. 5<sup>th</sup> 2016 Hamburg  
Room Acoustics, PA Systems and Speech Intelligibility for Voice Alarm Systems by Anselm Goertz

V2016\_2  
Folie 41

## Final Measurements



### STIPA Summary Report

Report according to IEC 60268-16(ed4), chapter 7.6.4  
and DIN VDE 0833-4(2007-09), appendix F.6



|          |   |
|----------|---|
| Project  | Hamburg CC3   |
| Comments | Abreisehalle  |
| Standard | IEC 60268-16 ed4.0 2011   |
| All      | Arithmetic mean $\bar{X}$ STI 0,553<br>Standard deviation $\sigma$ STI 0,042<br><b>Total Result: <math>\bar{X} - \sigma</math> STI 0,51 G</b> |

- Completely empty hall without seating and without persons
- 60 measurement positions
- STI male with masking according to 60268-16 von 2011
- $STI_{avg-stdev} = 0,55 - 0,04 = 0,51$  (predicted 0,52)
- Max.SPL male speaker noise 12 dB crest factor: 86 dBA (predicted 84 dBA)

[www.ifaa-akustik.de](http://www.ifaa-akustik.de)

Manuscript to this presentation with text and graphics as PDF file