Next steps in wind tunnel aeroacoustics: Measurements at flight-Reynolds numbers

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Acknowledgments

Aeroacoustic Measurement Technique Group Göttingen

- Measurements in WT and flight tests
- (Dr. Lars Koop), Dr. Carsten Spehr, Dr. Thomas Ahlefeldt, Dr. Stefan Haxter, Daniel Ernst, Hans-Georg Raumer

Federal Ministry of Economics and Technology

- Financial support

European Transonic Windtunnel

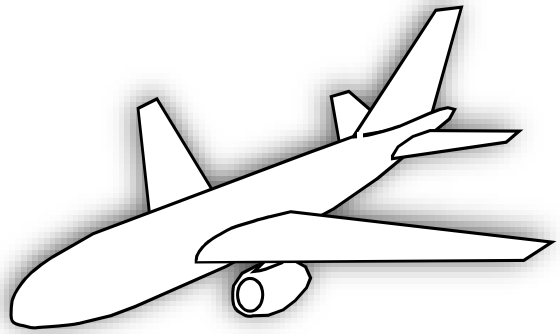
- Provided Infrastructure
- Jürgen Quest: project leader

Airbus

- Provision of the model
- Iris Goldhahn: cooperation

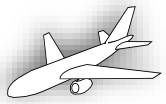
Background

Original



$Re \approx 20$ Mio

Scaled model in Wind Tunnel



standard	cryogenic or pressurized	cryogenic and pressurized
$Re \approx 1.4$ Mio	$Re \approx 5.2$ Mio	$Re \approx 20$ Mio

- Model fidelity
- Installation effects
- Reynolds number, Mach number, Strouhal number

(Drawings adapted from Prof. Asai K, Tohoku University, Sendai, Japan)

Previous work

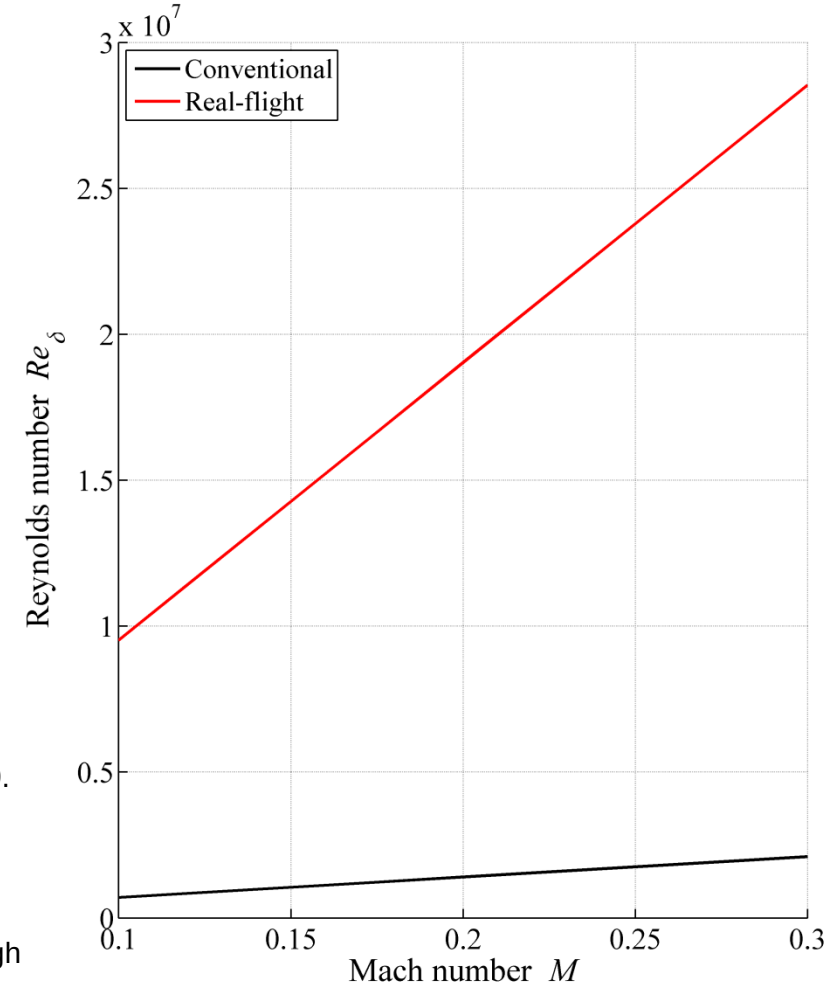
$$\mathrm{Re} = \frac{\rho \cdot u_\infty \cdot d}{\eta} = \frac{\rho \cdot \mathrm{M} \cdot d}{c \cdot \eta}$$

Aeroacoustic measurements in wind tunnels

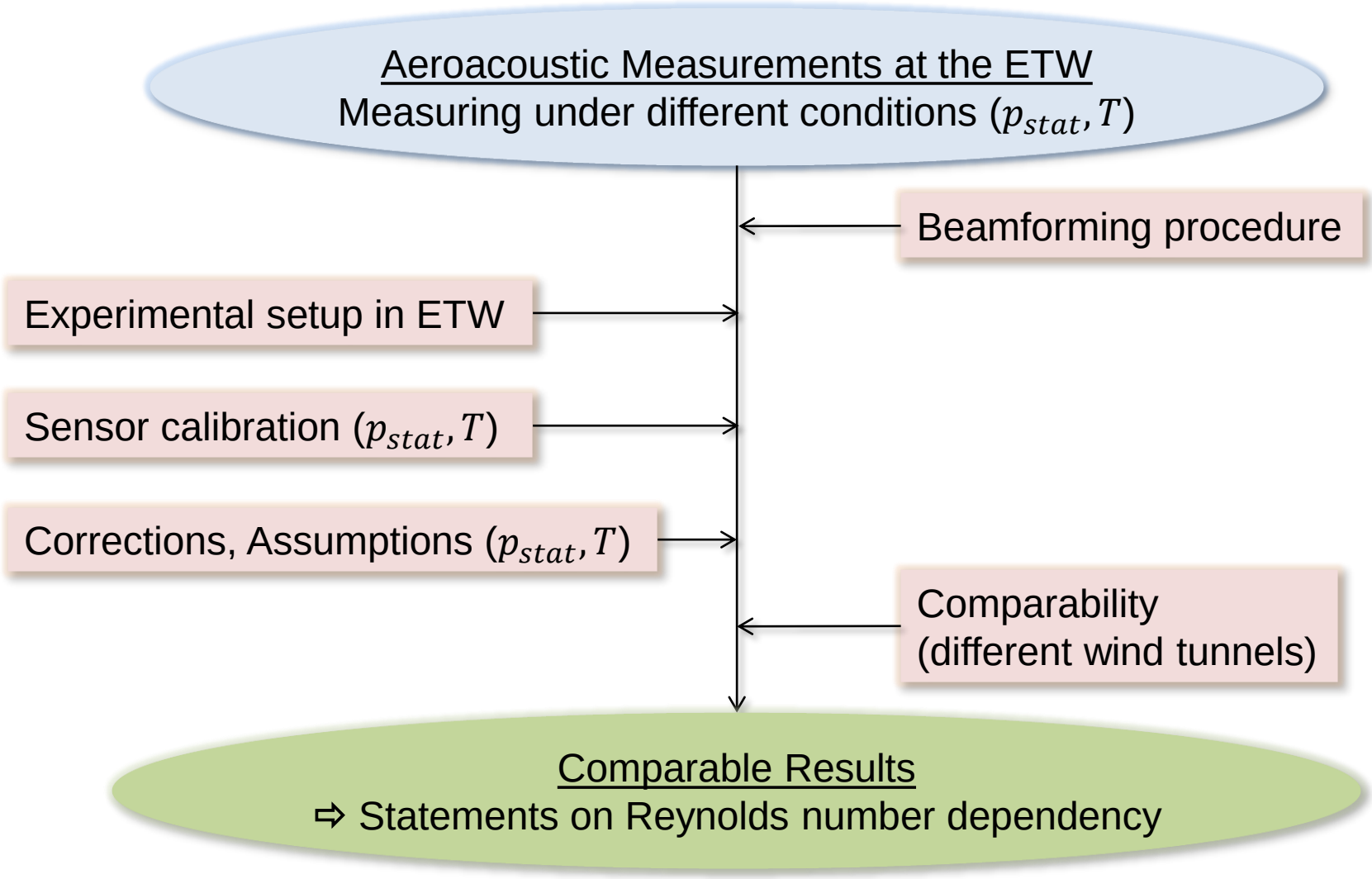
Hayes [1999] at NTF
- Pressurized environment

Stoker [2008] at NTF
- Pressurized and mild cryogenic ($T = 226.5$ K)

Ahlefeldt [2010] at DNW-KKK
- Cryogenic ($T = 100$ K)



[1] Hayes, J. A. et. al., „Measurement of Reynolds number effects on airframe noise in the 12-foot pressure wind tunnel", *5th AIAA/CEAS*, 1999.
[2] Stoker, R.W. et. al., "High Reynolds Number Aeroacoustic Testing in NASAs National Transonic Facility (NTF)", *46th AIAA-ASM*, 2008.
[3] Ahlefeldt T. and Koop L., "Microphone-Array Measurements in a Cryogenic Wind Tunnel", *AIAA-Journal,* Vol.48, No.7, 2010.
[4] Ahlefeldt T., "Aeroacoustic Measurements of a Scaled Half Model at High Reynolds Numbers", *AIAA-Journal,* Vol.51, No.12, 2013.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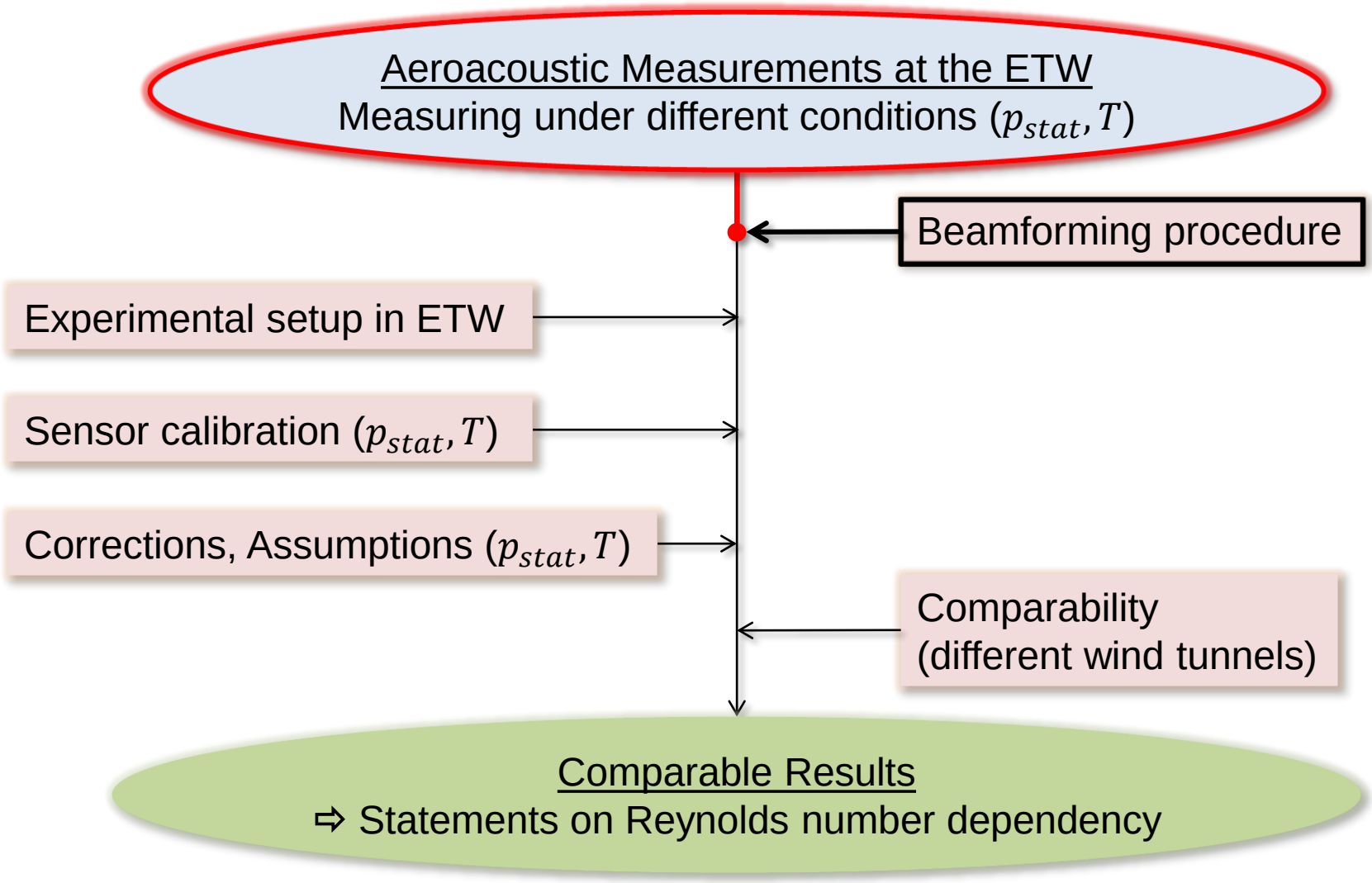
Measuring under different conditions (p_{stat}, T)
Beamforming procedure
Experimental setup in ETW
Sensor calibration (p_{stat}, T)
Corrections, Assumptions (p_{stat}, T)
Comparability
(different wind tunnels)
Comparable Results
⇨ Statements on Reynolds number dependency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Background: acoustic sources in beamforming

Numerical approach

$$\frac{\partial}{\partial t^2}\rho' - c^2\Delta\rho' = \frac{\partial^2}{\partial x_i x_j}T_{ij}$$

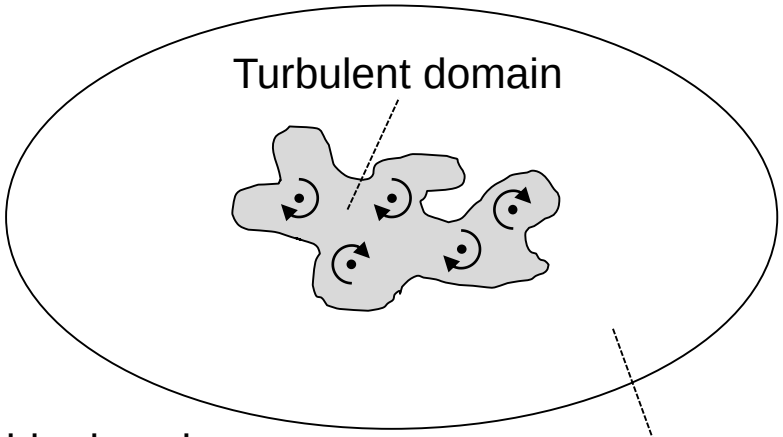
Lighthill equation

⇒"Equivalent sources"

Application:

$$\rho' = \frac{1}{4\pi c^2}\frac{\partial^2}{\partial x_i x_j}\int_{V_Q}\frac{T_{ij}(\boldsymbol{y}, t-|\boldsymbol{x}-\boldsymbol{y}|/c^2)}{|\boldsymbol{x}-\boldsymbol{y}|}d^3\boldsymbol{y}$$

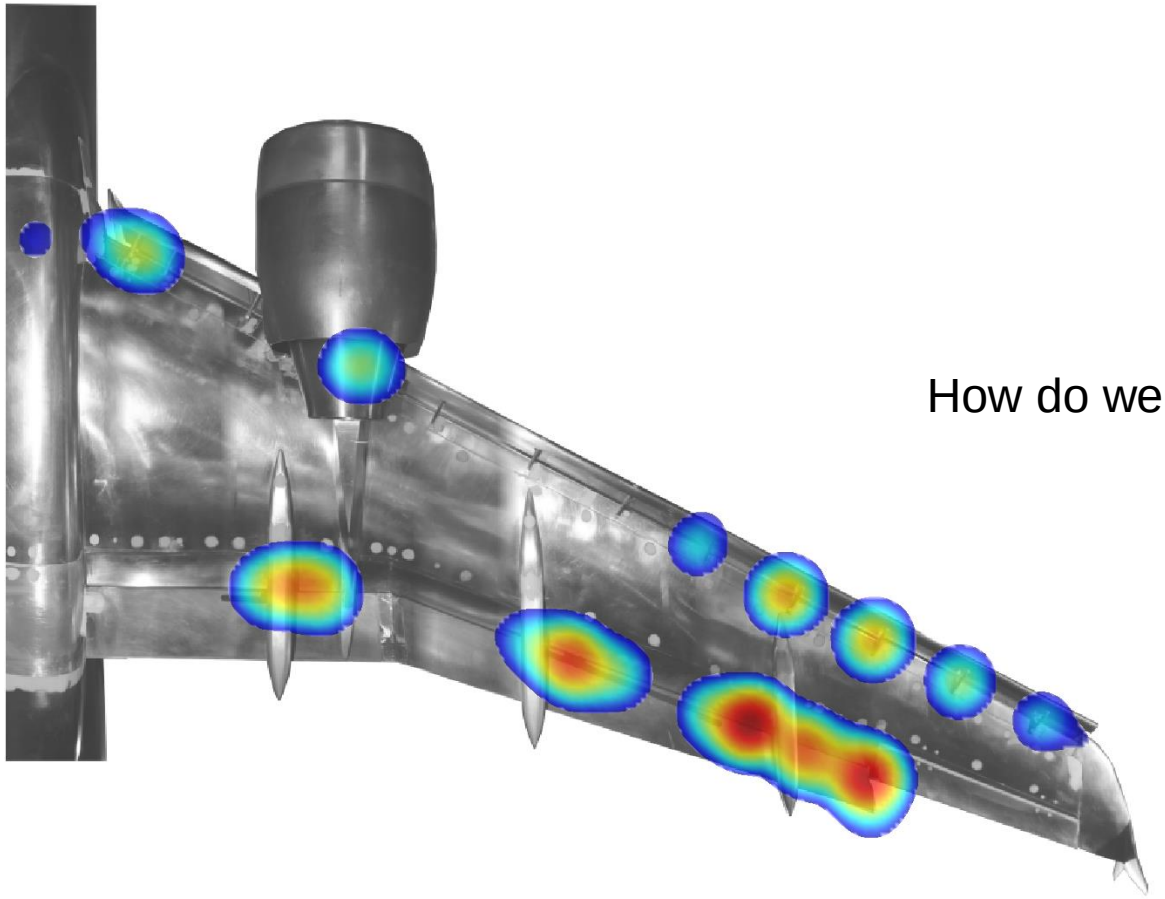
Approximate solution without boundaries



Outside domain:
no flow, $Q = 0$

V_Q: Domain with non-linear effects

Background: acoustic sources in beamforming
Beamforming approach

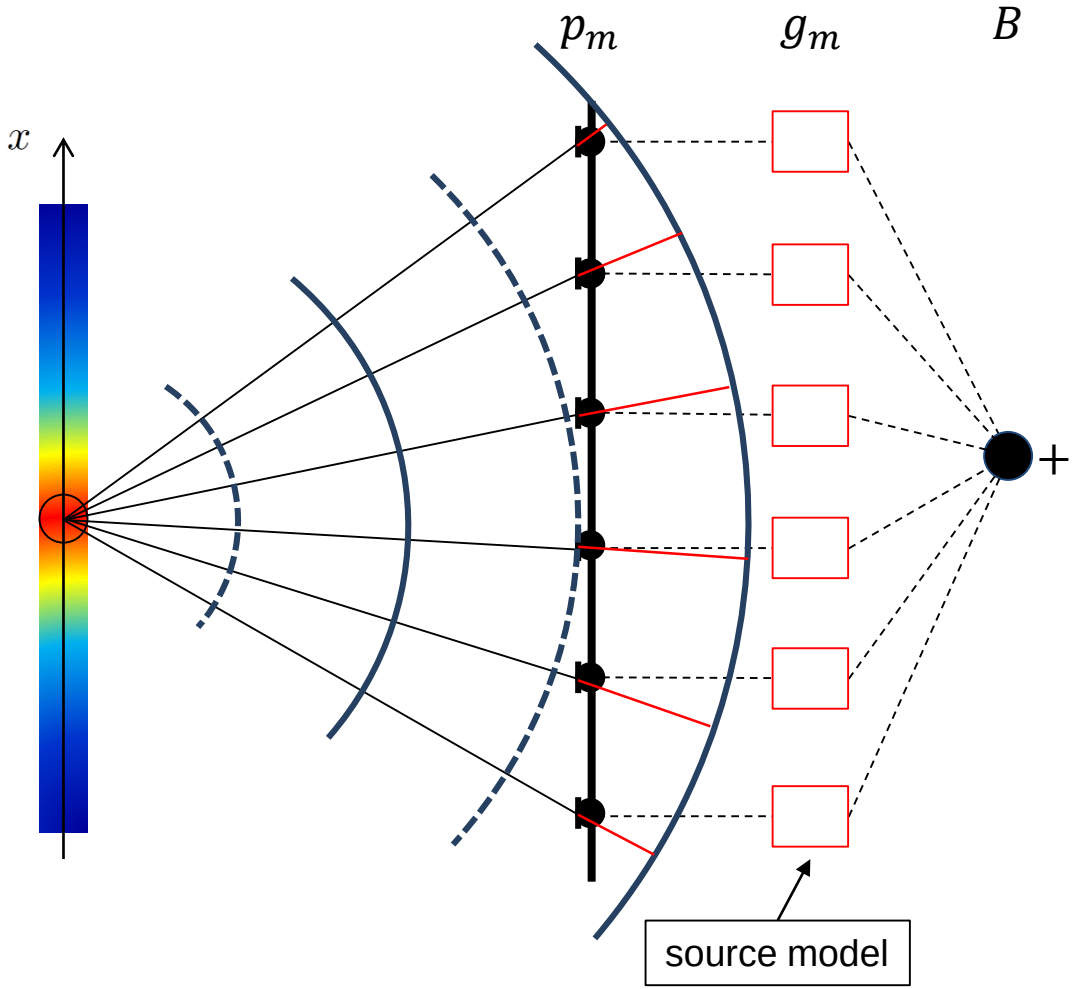


How do we obtain source maps ?

Background: acoustic sources in beamforming

Beamforming approach – time domain

$$B = \sum_{m=1}^{M} p_m \, g_m$$



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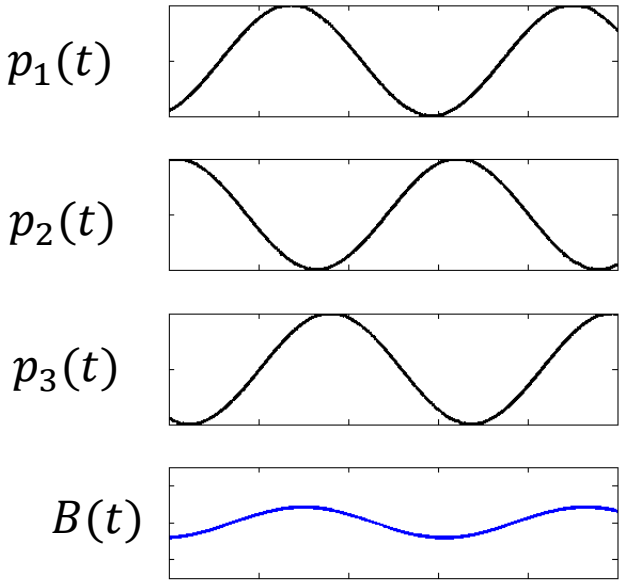
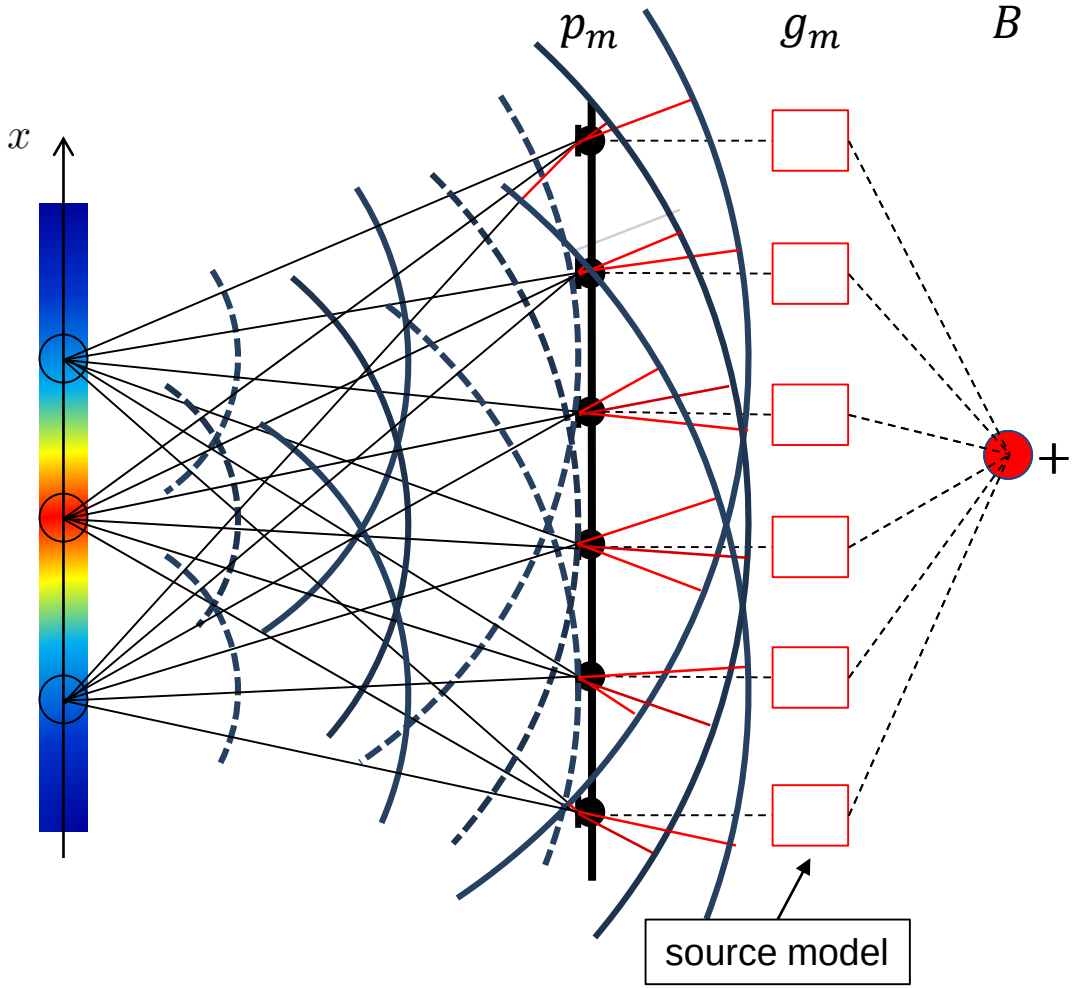
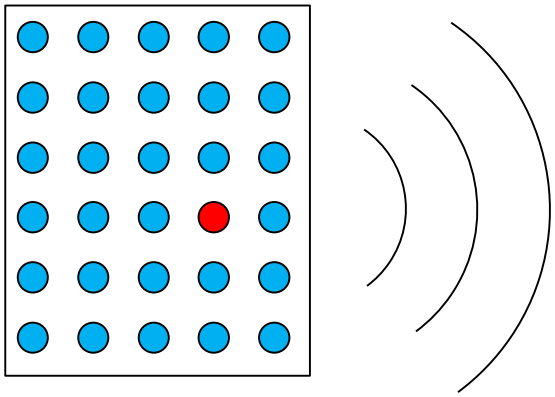




Background: acoustic sources in beamforming
Beamforming approach – frequency domain

Map domain
with focus points y_n

Microphones in
far field x_m



Pressure signals and cross spectral matrix
(sampled in time blocks k)

$$\boldsymbol{p}^{(k)}(\omega) = \begin{pmatrix} p_1^{(k)}(\omega) \\ \vdots \\ p_M^{(k)}(\omega) \end{pmatrix}$$

$$\boldsymbol{C}(\omega) = \frac{1}{K}\sum_{k=1}^{K} \boldsymbol{p}^{(k)}(\omega)\boldsymbol{p}^{(k)}(\omega)^*$$

Green's function of
convective Helmholtz equation

$$g = \frac{e^{-j\omega\Delta t}}{4\pi\sqrt{\left(\boldsymbol{M}\cdot(\boldsymbol{x}-\boldsymbol{y})\right)^2 + \beta^2\|\boldsymbol{x}-\boldsymbol{y}\|^2}}$$

with $\beta^2 = 1 - \|\boldsymbol{M}\|^2$

Steering vector and steering matrix

$$\boldsymbol{g}(\boldsymbol{y},\omega) = \begin{pmatrix} g_1(\omega, x_1, \boldsymbol{y}) \\ \vdots \\ g_M(\omega, x_M, \boldsymbol{y}) \end{pmatrix}$$

$$\boldsymbol{G}(\boldsymbol{y},\omega) = \boldsymbol{g}(\boldsymbol{y},\omega)\boldsymbol{g}(\boldsymbol{y},\omega)^*$$

Background: acoustic sources in beamforming

Beamforming approach – frequency domain

Map domain
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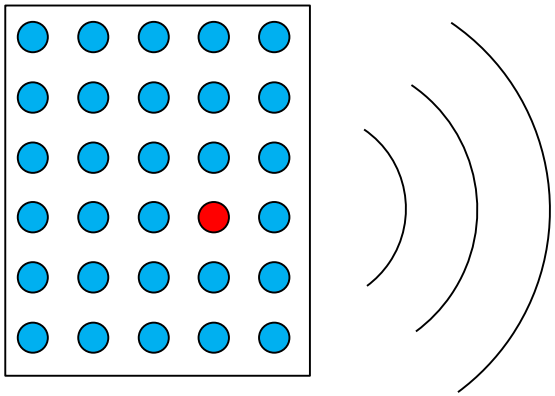


Microphones in
far field x_m

Cross spectral matrix

$$\boldsymbol{C}(\omega) = \frac{1}{K}\sum_{k=1}^{K} \boldsymbol{p}^{(k)}(\omega)\boldsymbol{p}^{(k)}(\omega)^*$$

Steering matrix

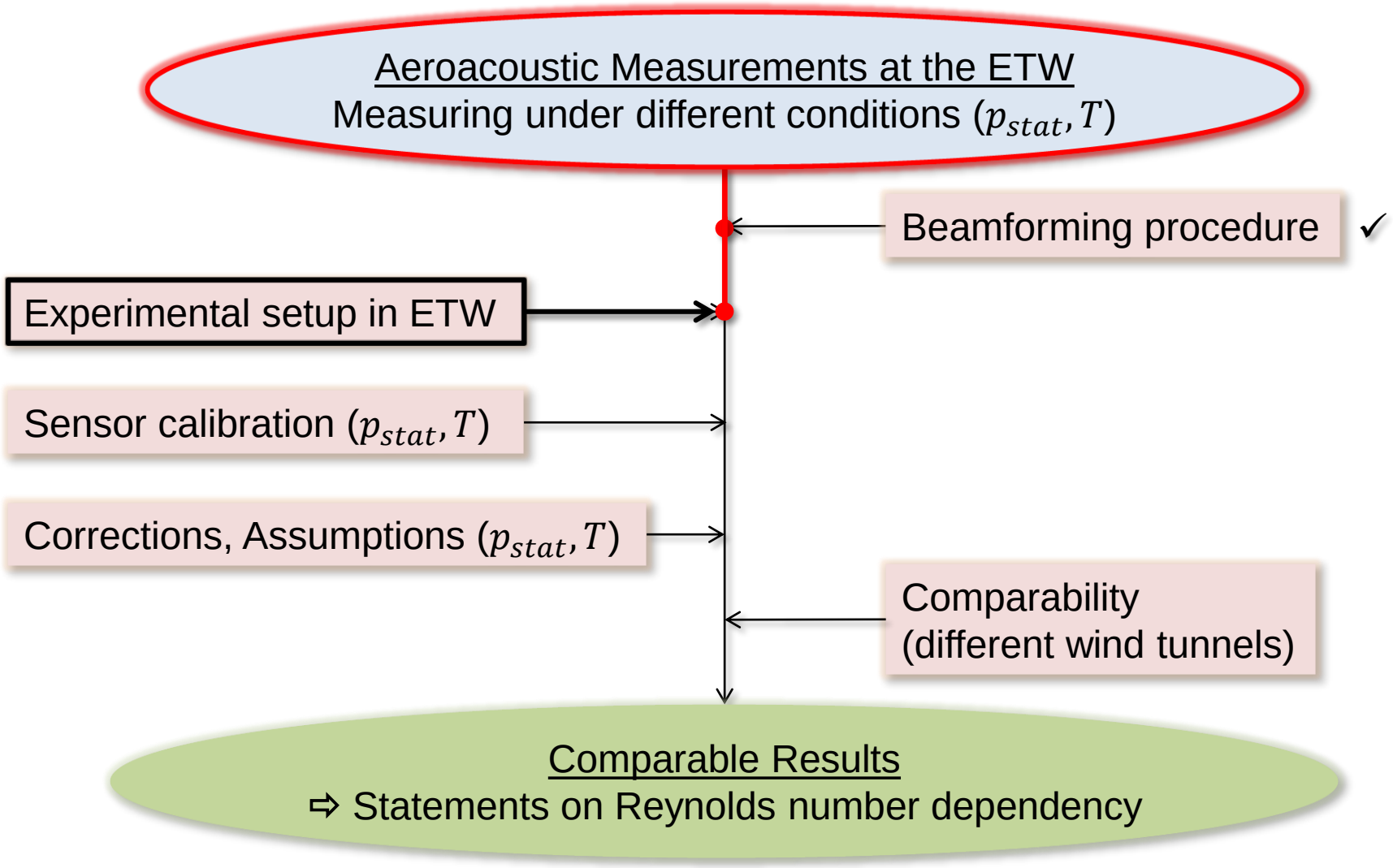
$$\boldsymbol{G}(\boldsymbol{y},\omega) = \boldsymbol{g}(\boldsymbol{y},\omega)\boldsymbol{g}(\boldsymbol{y},\omega)^*$$

Minimization problem

$$\min_{\mu\in\mathbb{R}} \|\boldsymbol{C}(\omega) - \mu\boldsymbol{G}(y,\omega)\|_F$$

Unique solution (Conventional Beamforming)

$$\boldsymbol{B}(\boldsymbol{y},\omega) = \frac{\boldsymbol{g}(\boldsymbol{y},\omega)^*\boldsymbol{C}(\omega)\boldsymbol{g}(\boldsymbol{y},\omega)}{\|\boldsymbol{g}(\boldsymbol{y},\omega)\boldsymbol{g}(\boldsymbol{y},\omega)^*\|_F^2}$$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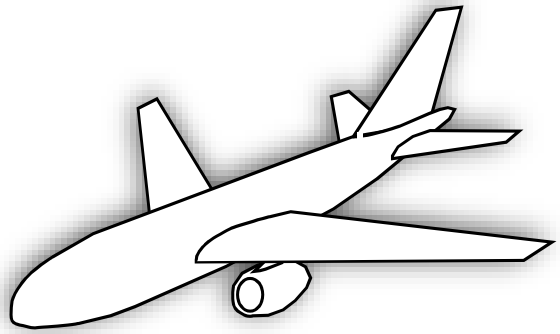
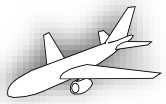
Background

Original



$Re \approx 20$ Mio

Scaled model in Wind Tunnel



standard	cryogenic or pressurized	cryogenic and pressurized
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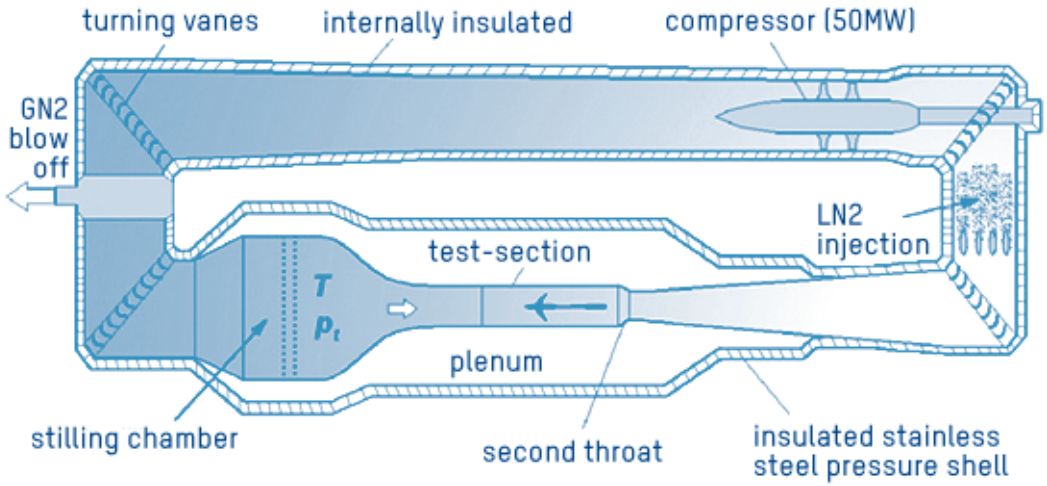
- Model fidelity
- Installation effects
- Reynolds number, Mach number, Strouhal number

(Drawings adapted from Prof. Asai K, Tohoku University, Sendai, Japan)

Wind Tunnel

- European Transonic Windtunnel (ETW)
- Provision of real-flight Reynolds numbers by virtue of both decreased temperature and increased pressure
- Test section:
  $2.0\ \mathrm{m} \times 2.4\ \mathrm{m} \times 9.0\ \mathrm{m}$
- Operational range:

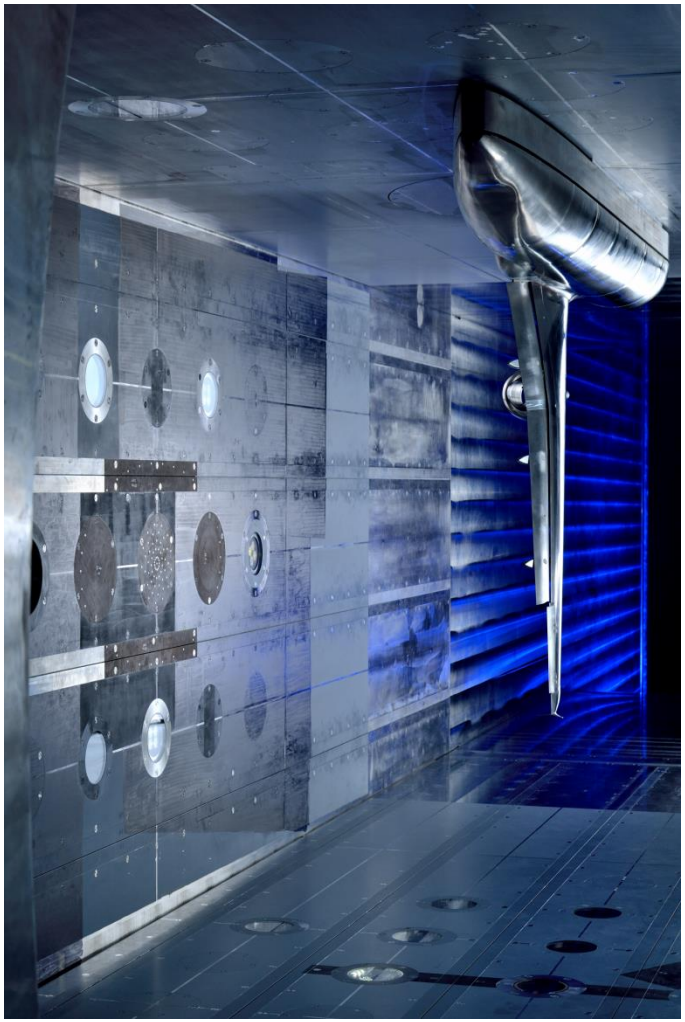
$0.15 < M < 1.35$
$313\ \mathrm{K} > T > 110\ \mathrm{K}$
$110\ \mathrm{kPa} < p_{stat} < 450\ \mathrm{kPa}$



Setup

Airbus K3DY half-model

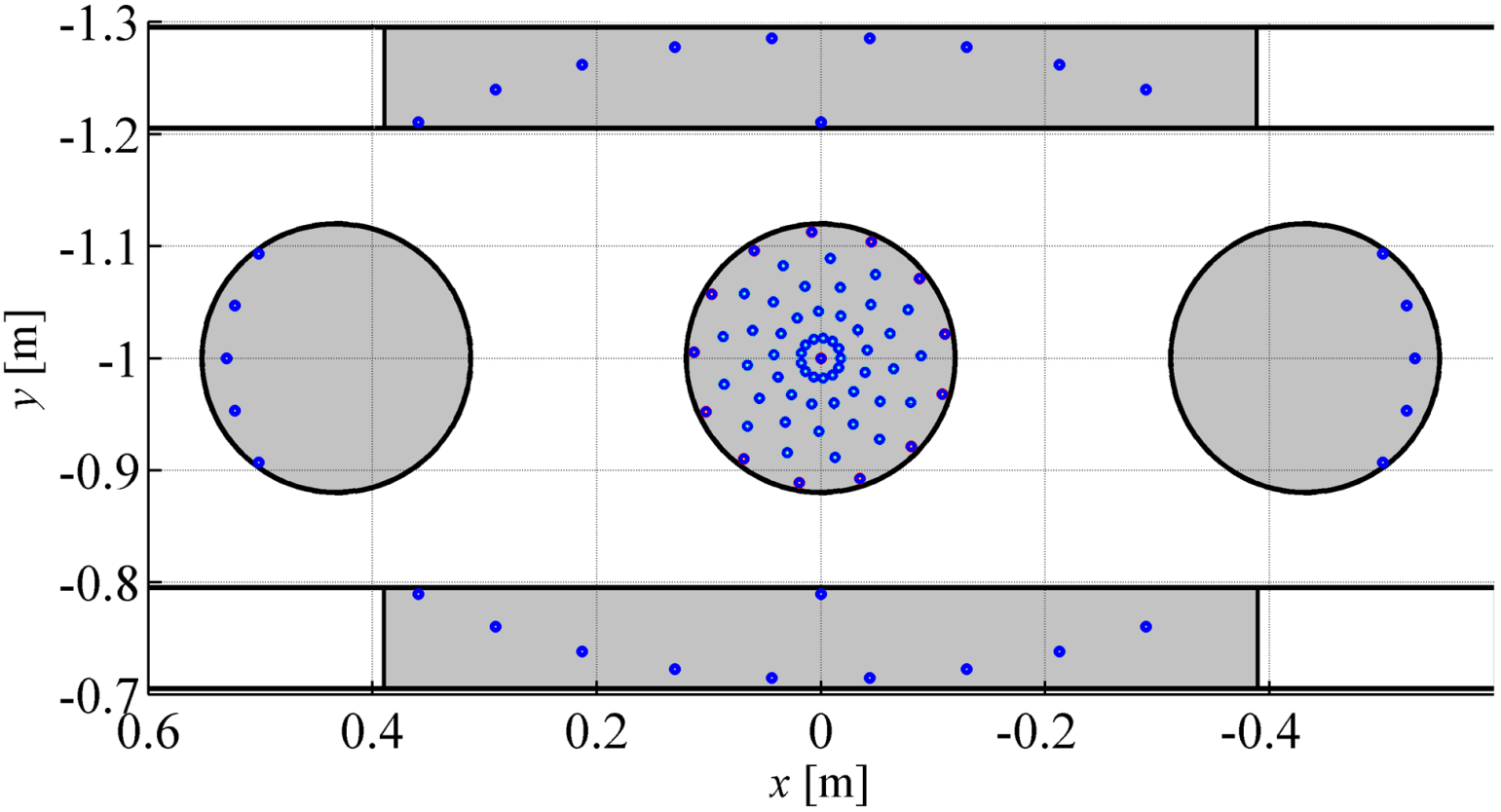
- Scale: 1:13.6 (7.35%), $\delta \approx 0.3$ m
- Slat: 26 deg, Flaps: 34 deg
- High-lift configuration identical to EWA-Benchmark test 2007 at LSWT



*Ahlefeldt T., “Aeroacoustic Measurements of a Scaled Half-Model at High Reynolds Numbers”, *AIAA Journal*, Vol. 55, No. 1 (2017).

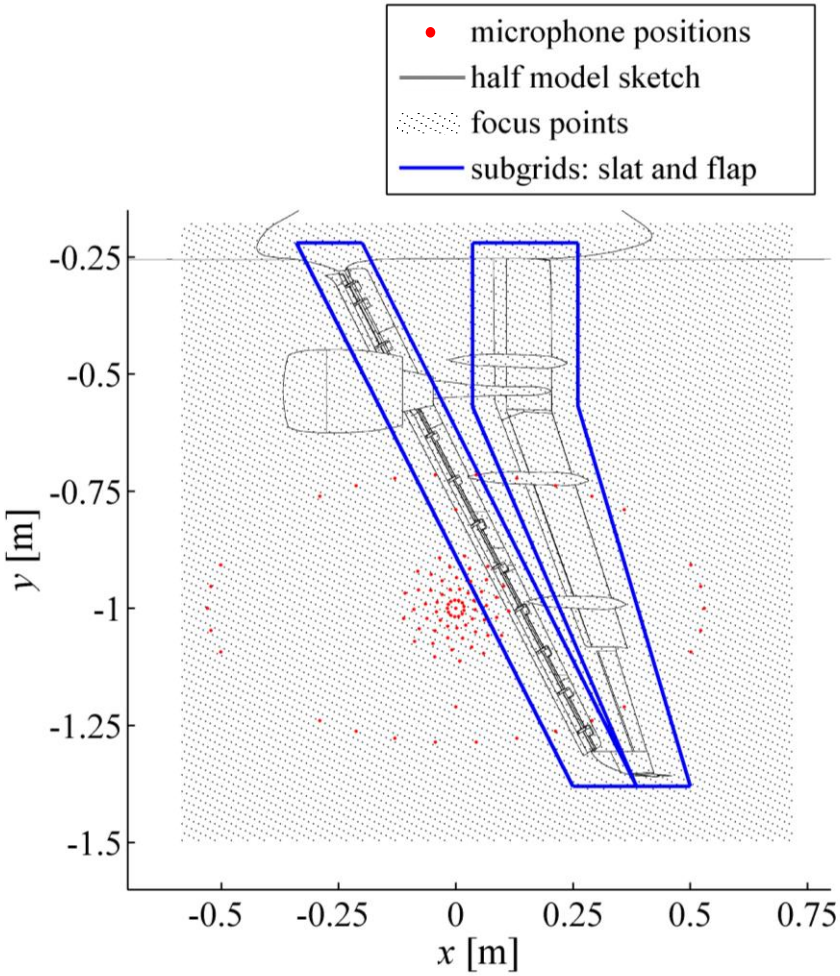
Setup

- Limited positioning of microphones:
  - Significantly restricted angle/area of observation



Data processing

- Algorithms:
  - Conventional beamforming with DR
  - Increased dynamic range: CLEAN-SC*
- Speed of sound: function of temperature and pressure
- Observation plane: $1.30\ \mathrm{m} \times 1.32\ \mathrm{m}$ ($d_{xy} = 5\ \mathrm{mm}$, 69165 grid points)
- Grid rotated with α and dihedral angle



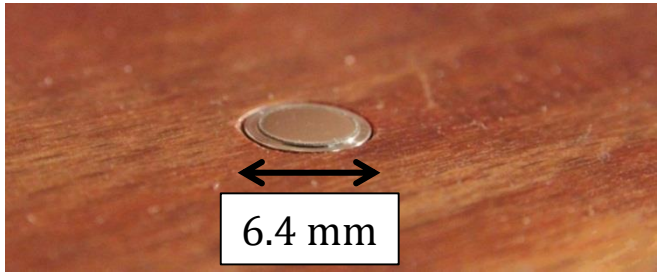
*Sijtsma P., “CLEAN based on spatial source coherence”, *International Journal of Aeroacoustics*, Vol 6, 2012.

Setup

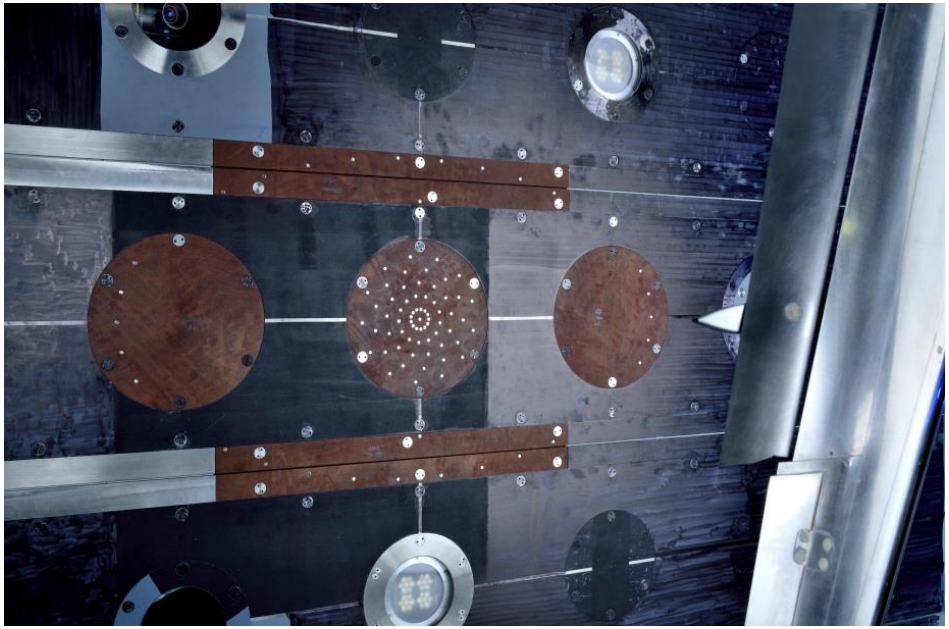
Microphone-Array

- 96 microphones (flush mounted)
- Inserts: compressed laminated wood

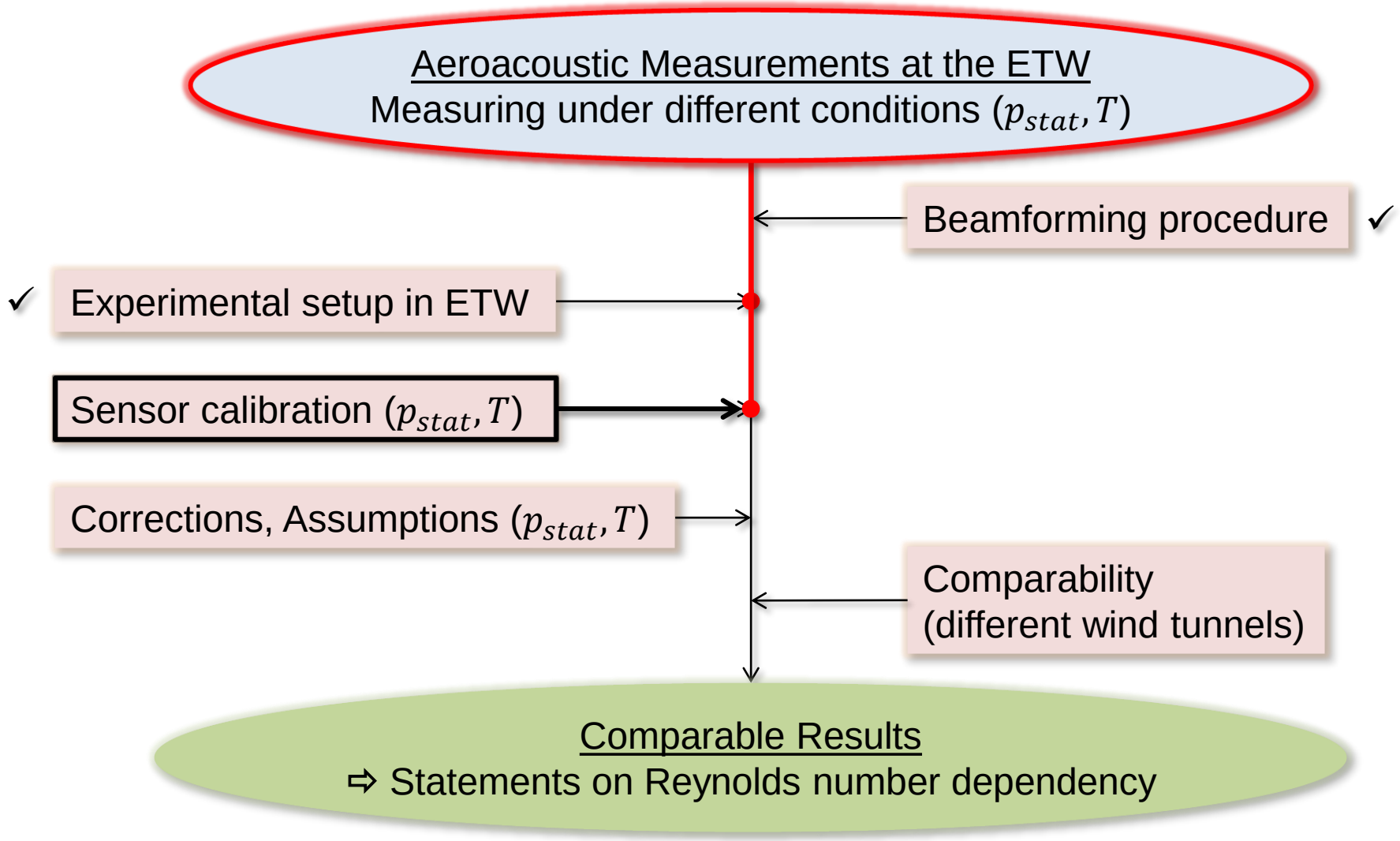
Brüel&Kjær cryogenic-type 4944A



Microphone membrane on test section wall



Microphone array integrated in test section wall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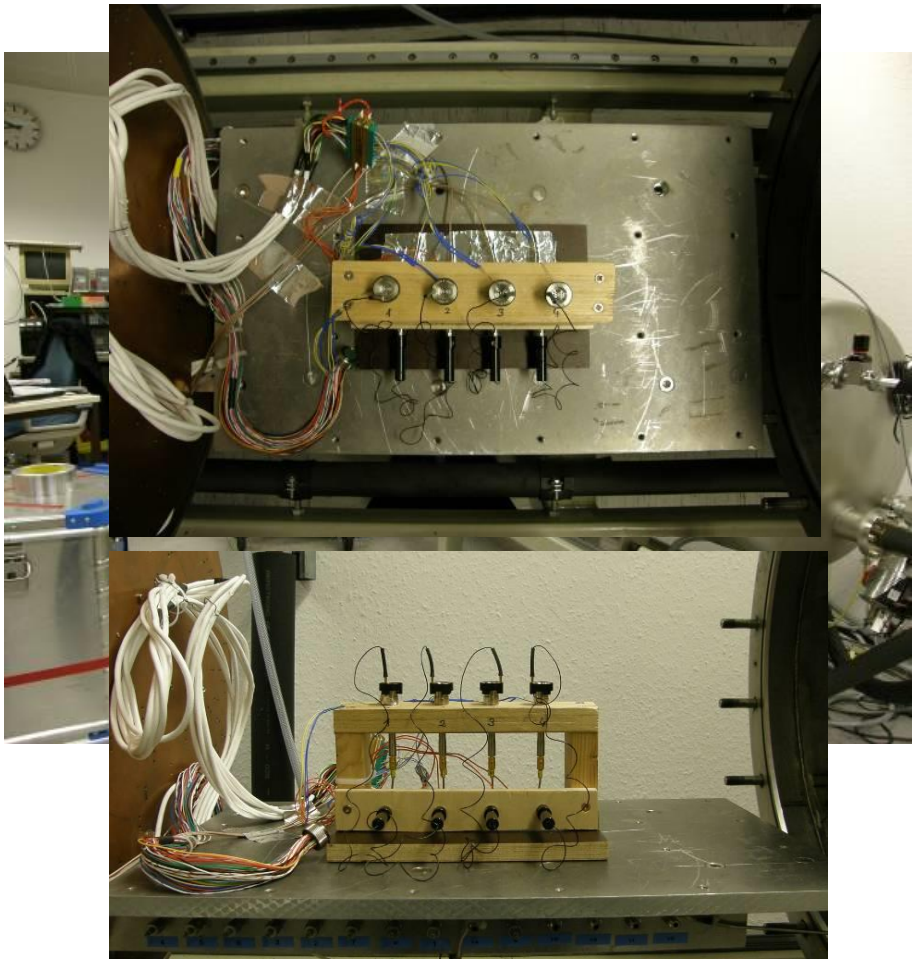
Sensor calibration

Cryogenic vessel of the ETW

- $120\ \mathrm{K} \leq T \leq 290\ \mathrm{K}$
- $100\ \mathrm{kPa} \leq p_{stat} \leq 400\ \mathrm{kPa}$

Measurements

- 4 microphones (B&K cryogenic-type 4944A)
- PULSE measurement system (Brüel&Kjær)
- Excitation: electrostatic actuator $f_{exc} = 1\ \mathrm{kHz}$ to $100\ \mathrm{kHz}$

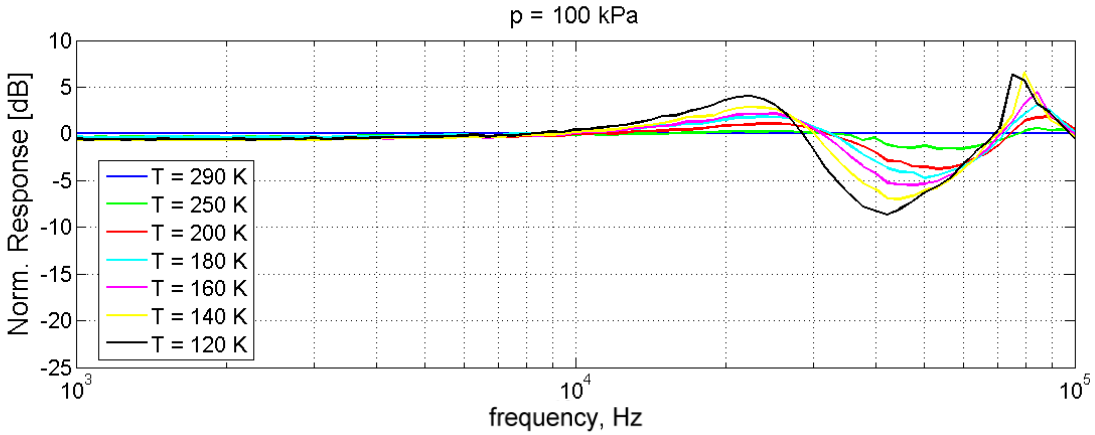


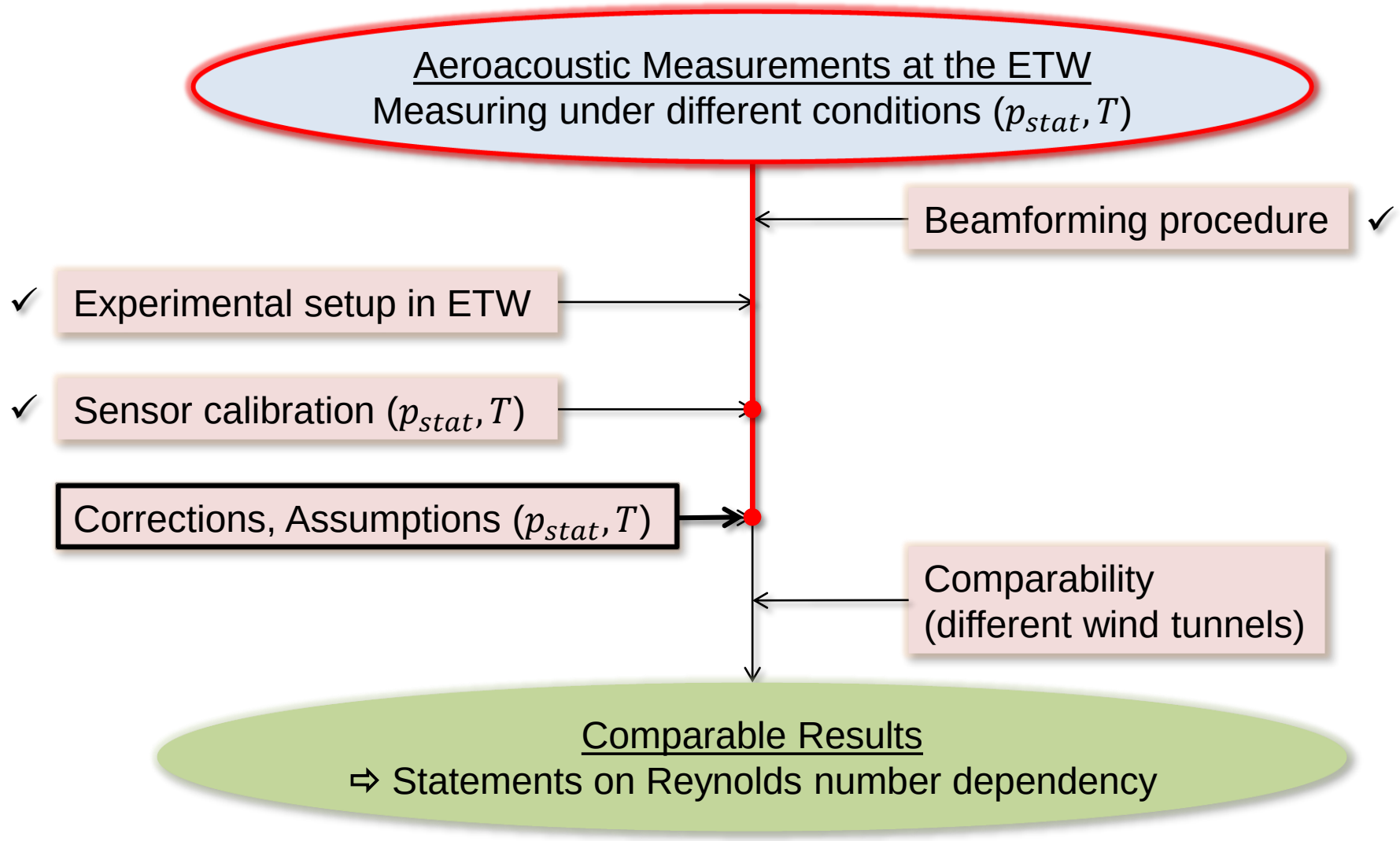
Ahlefeldt T. and Quest J. ”High-Reynolds Number Aeroacoustic Testing under Pressurized Cryogenic Conditions in PETW”, *50th AIAA-ASM*, 2012

Sensor calibration – frequency response

$$p_{stat} = 100\ \text{kPa}$$
$$120\ \text{K} \leq T \leq 290\ \text{K}$$

- wavy frequency response with several resonances

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$$M = {}^{u}/_{c}$$
$$St = {}^{fD}/_{u}$$
$$He = {}^{2\pi fD}/_{c}$$

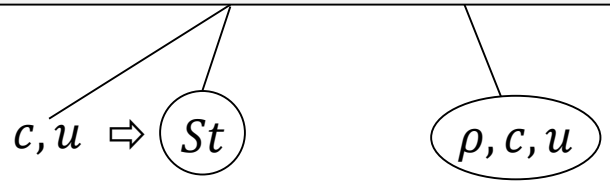
Corrections / Assumptions

- Aeroacoustic similarity:
  Reynolds number, Mach number, Strouhal number, (Helmholtz number)

- Conditions
  - Change of static pressure p_{stat} and temperature T
  - $M = \frac{u}{c} = const.$

⇨Change of density ρ, speed of sound c, flow speed u, Reynolds number Re

Source mechanisms: $p' = \text{function}(frequency, amplitude, Reynolds\ number)$



Corrections / Assumptions
Amplitude

Dipole*

- Compact source in far-field: $I \propto \frac{\rho u_\infty^6}{c^3} \frac{D^2}{r^2} f(Re)$

*Curle N., “The Influence of Solid Boundaries upon Aerodynamic Sound”, *Proc. R. Soc. Lond., A*, Vol 231 (1955).

#Lighthill M.J., “On sound generated aerodynamically I. General theory”, *Proc. R. Soc. Lond., A*, Vol 211 (1952).

Ahlefeldt T., “Aeroacoustic Measurements of a Scaled Half-Model at High Reynolds Numbers”, *AIAA Journal*, Vol. 55, No. 1 (2017).

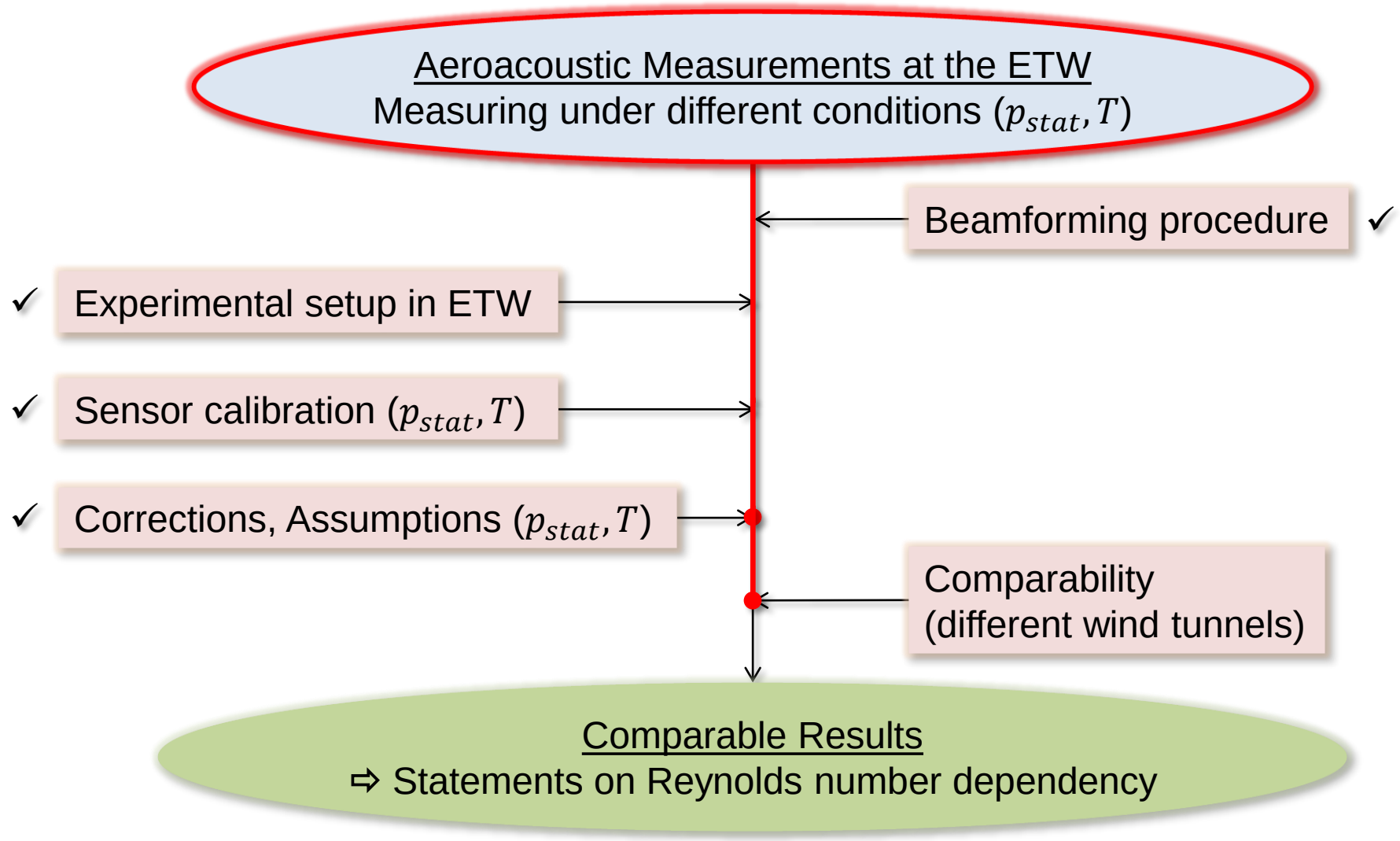
Corrections / Assumptions

- Aeroacoustic similarity:
  Reynolds number, Mach number, Strouhal number, (Helmholtz number)
- Source mechanisms: $p' = \text{function}(frequency, amplitude, Reynolds\ number)$
- Comparison at $M = \text{const.}$

St

ρ, c, u

$$\Delta dB = 20 log_{10}\left(\frac{\rho c^2}{\rho_0 c_0^2}\right)$$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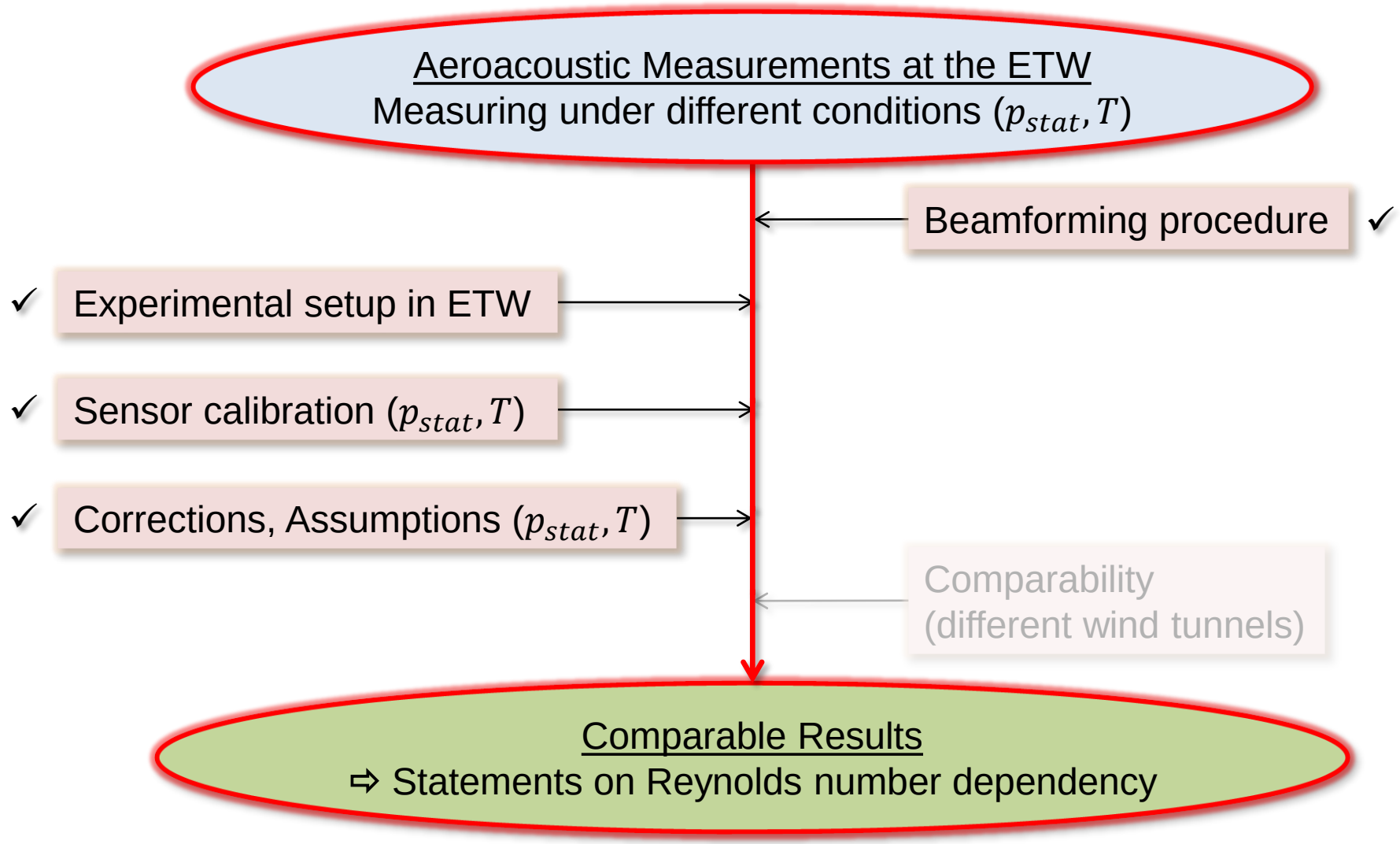
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Results – Source maps (CLEAN-SC)

M = 0.203 | α = 3° | Variation of Strouhal number

$Re_\delta = 1.42 \cdot 10^6$

$Re_\delta = 5.16 \cdot 10^6$

$Re_\delta = 20.0 \cdot 10^6$

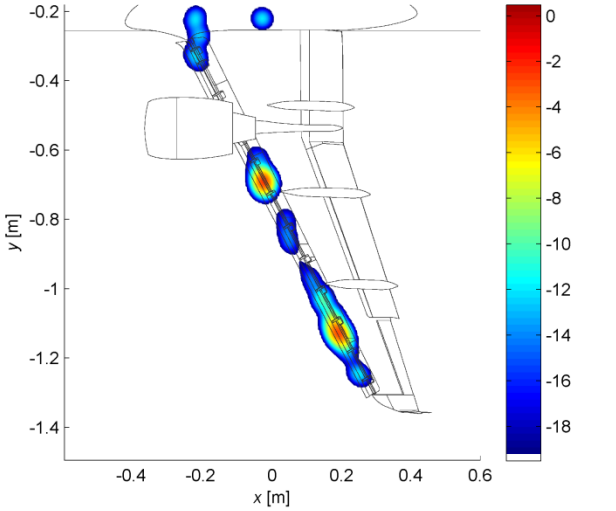
Results – Source maps (CLEAN-SC)

M = 0.203 | α = 3° | Variation of Strouhal number

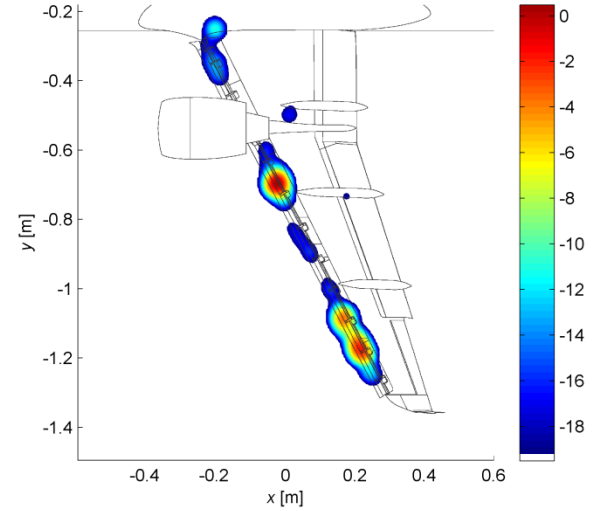
$$St_{\delta,1/3Oct} = 20 \mid f_{full-scale} = 335\ \text{Hz}$$

$Re_\delta = 1.42 \cdot 10^6$ | $Re_\delta = 5.16 \cdot 10^6$ | $Re_\delta = 20.0 \cdot 10^6$

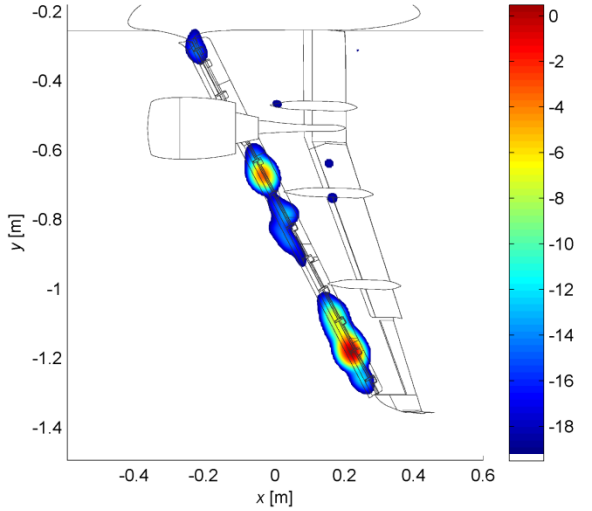
$St_{1/3Oct} = 20\ (4.7\ \text{kHz}) \mid T = 311\ \text{K} \mid p = 110\ \text{kPa}$



$St_{1/3Oct} = 20\ (4.8\ \text{kHz}) \mid T = 311\ \text{K} \mid p = 399\ \text{kPa}$



$St_{1/3Oct} = 20\ (3.0\ \text{kHz}) \mid T = 120\ \text{K} \mid p = 419\ \text{kPa}$



Quantitative comparison (identical scale), corrections applied

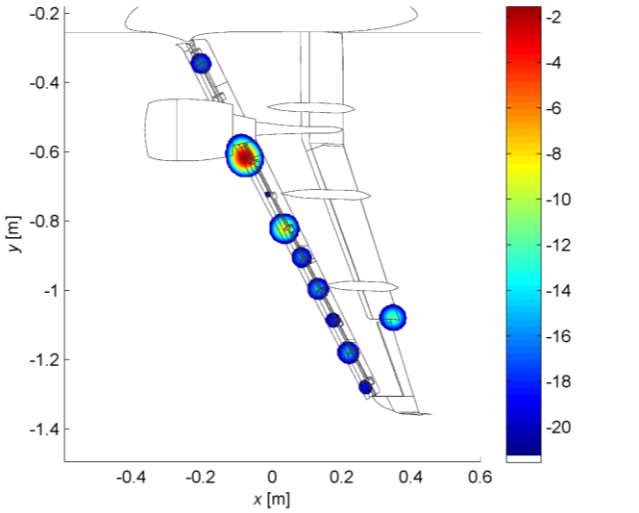
Results – Source maps (CLEAN-SC)

M = 0.203 | α = 3° | Variation of Strouhal number

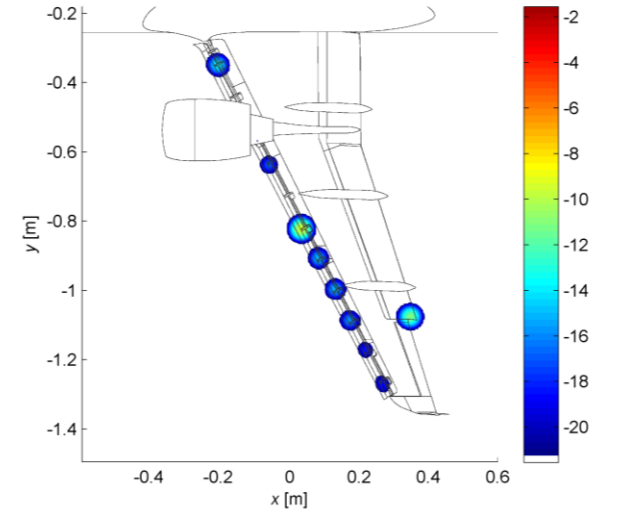
$$St_{\delta,1/3Oct} = 70 \mid f_{full-scale} = 1.2\ kHz$$

$Re_\delta = 1.42 \cdot 10^6$ | $Re_\delta = 5.16 \cdot 10^6$ | $Re_\delta = 20.0 \cdot 10^6$

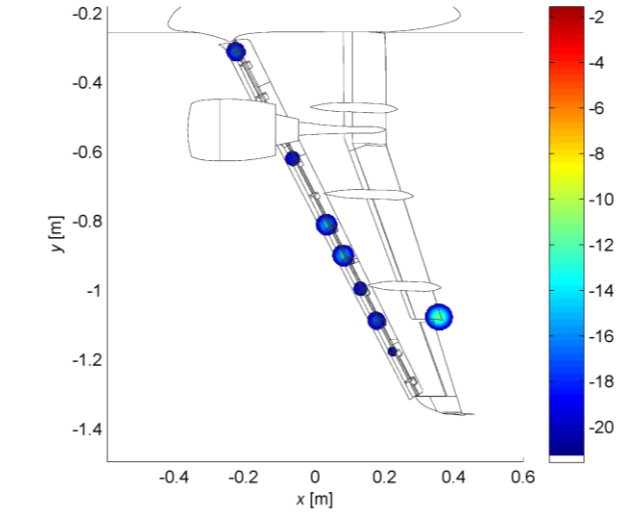
$St_{1/3Oct} = 70\ (16.5\ \text{kHz}) \mid T = 311\ \text{K} \mid p = 110\ \text{kPa}$



$St_{1/3Oct} = 70\ (16.6\ \text{kHz}) \mid T = 311\ \text{K} \mid p = 399\ \text{kPa}$



$St_{1/3Oct} = 70\ (10.5\ \text{kHz}) \mid T = 120\ \text{K} \mid p = 419\ \text{kPa}$



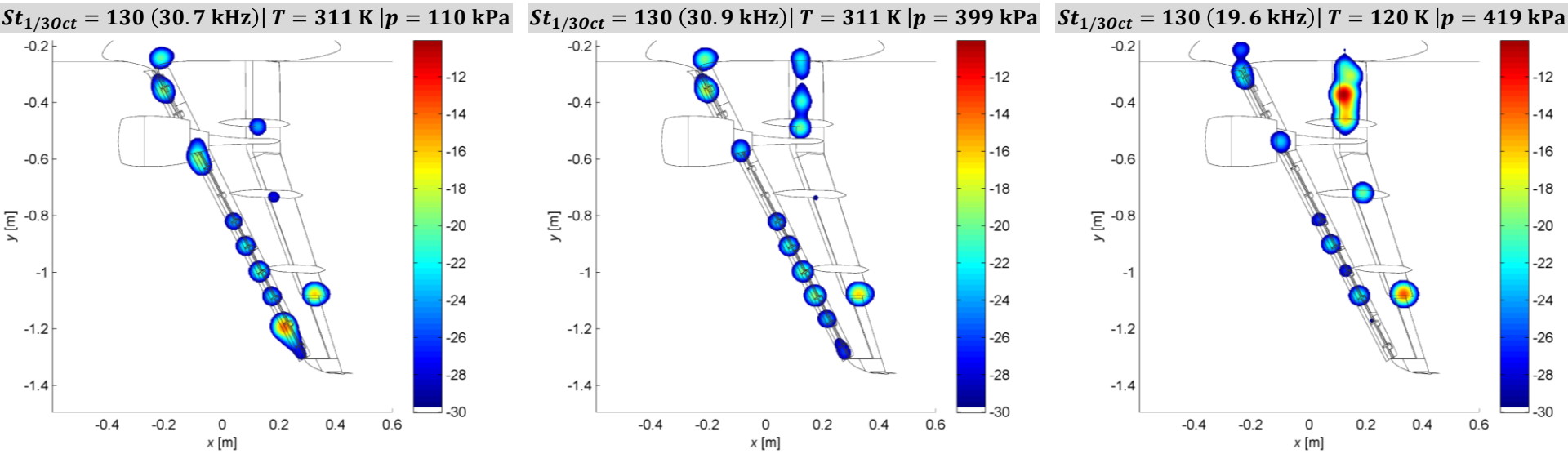
Quantitative comparison (identical scale), corrections applied

Results – Source maps (CLEAN-SC)

M = 0.203 | α = 3° | Variation of Strouhal number

$$St_{\delta,1/3Oct} = 130 \mid f_{full-scale} = 2.2\ kHz$$

$Re_\delta = 1.42 \cdot 10^6$ | $Re_\delta = 5.16 \cdot 10^6$ | $Re_\delta = 20.0 \cdot 10^6$



Quantitative comparison (identical scale), corrections applied

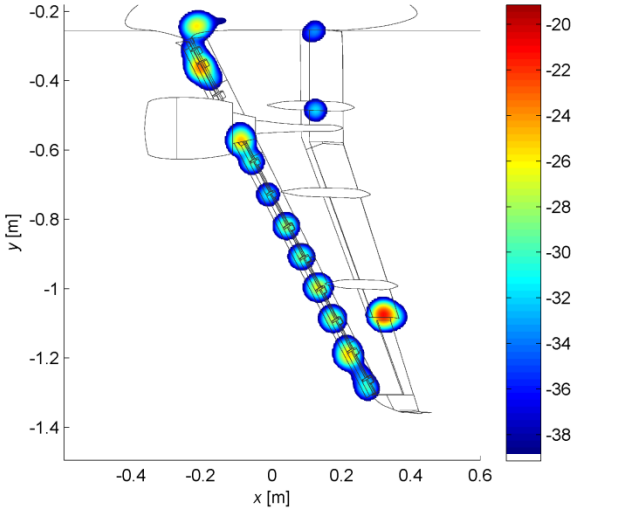
Results – Source maps (CLEAN-SC)

M = 0.203 | α = 3° | Variation of Strouhal number

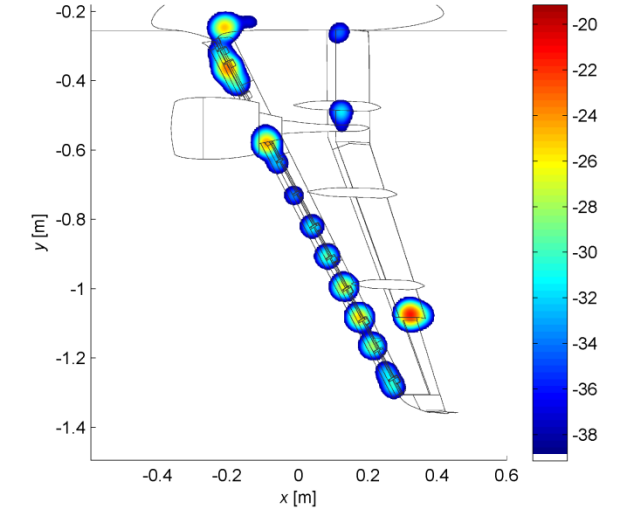
$$St_{\delta,1/3Oct} = 200 \mid f_{full-scale} = 3.4\ kHz$$

$Re_\delta = 1.42 \cdot 10^6$ | $Re_\delta = 5.16 \cdot 10^6$ | $Re_\delta = 20.0 \cdot 10^6$

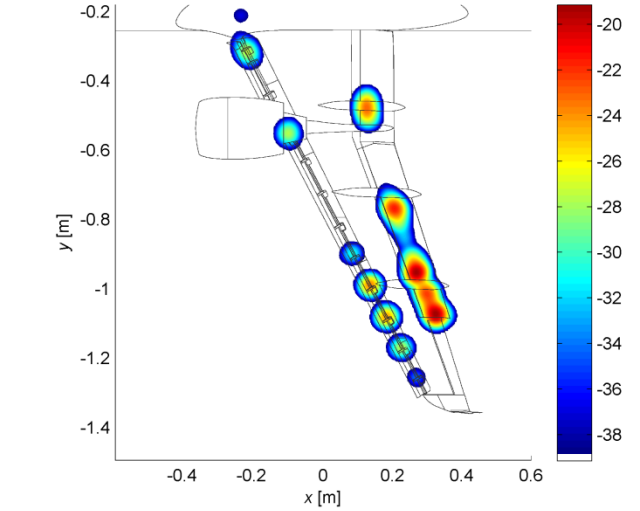
$St_{1/3Oct} = 200\ (47.3\ \text{kHz}) \mid T = 311\ \text{K} \mid p = 110\ \text{kPa}$



$St_{1/3Oct} = 200\ (47.5\ \text{kHz}) \mid T = 311\ \text{K} \mid p = 399\ \text{kPa}$

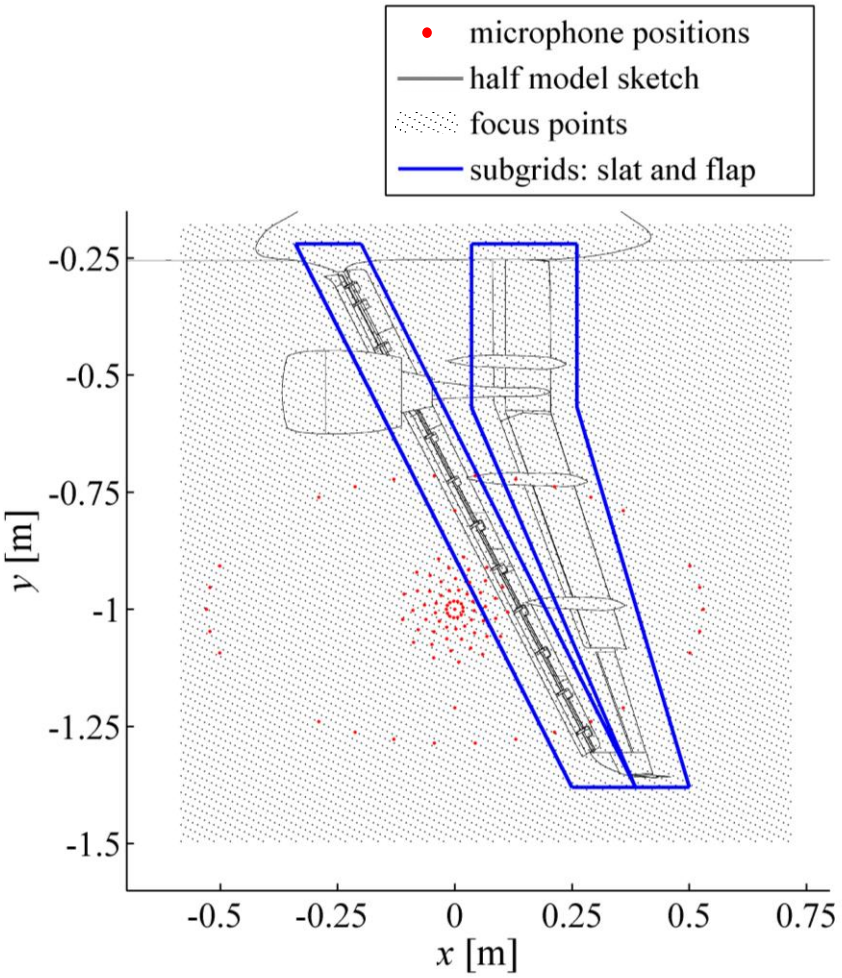


$St_{1/3Oct} = 200\ (30.1\ \text{kHz}) \mid T = 120\ \text{K} \mid p = 419\ \text{kPa}$



Quantitative comparison (identical scale), corrections applied

Results – Spectra: flap and slat

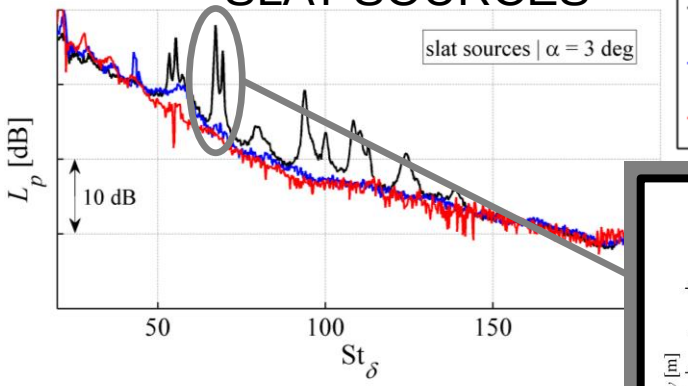


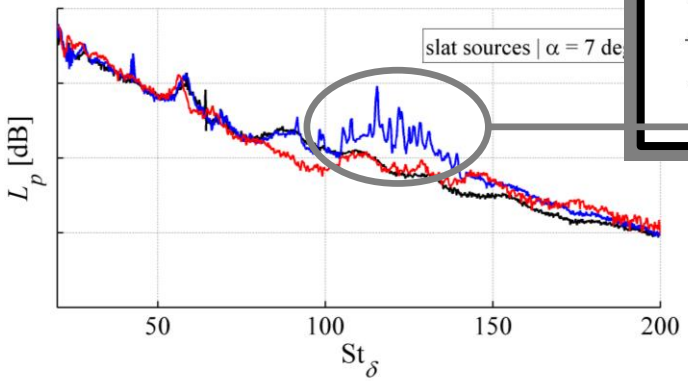
SLAT SOURCES

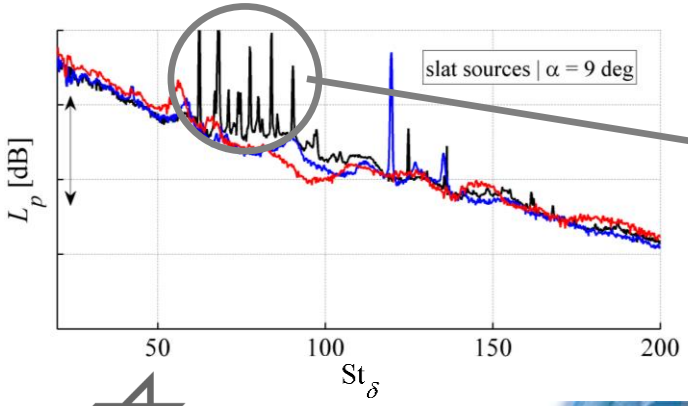
DP I: $Re_\delta = 1.43 \cdot 10^6 \mid q/E = 1.55 \cdot 10^{-8}$

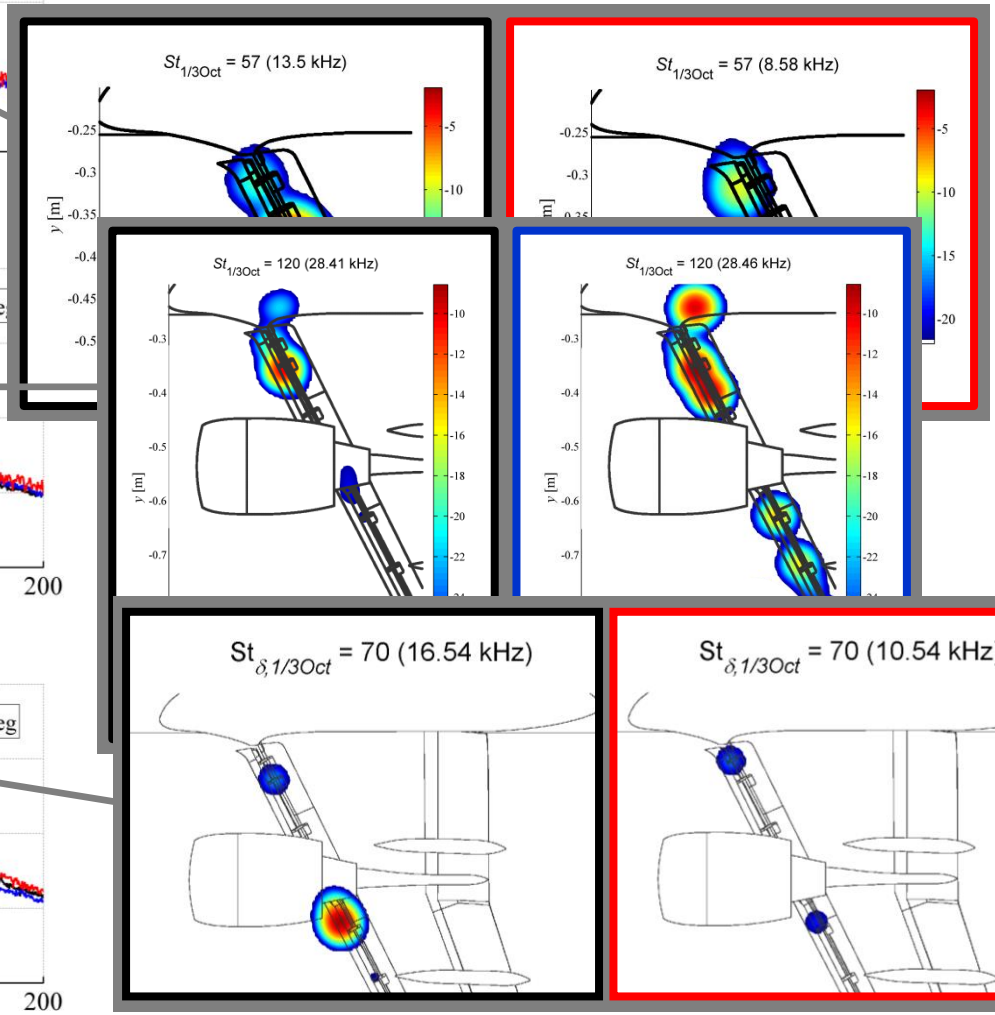
DP III: $Re_\delta = 5.17 \cdot 10^6 \mid q/E = 5.64 \cdot 10^{-8}$

DP IV: $Re_\delta = 20.06 \cdot 10^6 \mid q/E = 5.64 \cdot 10^{-8}$

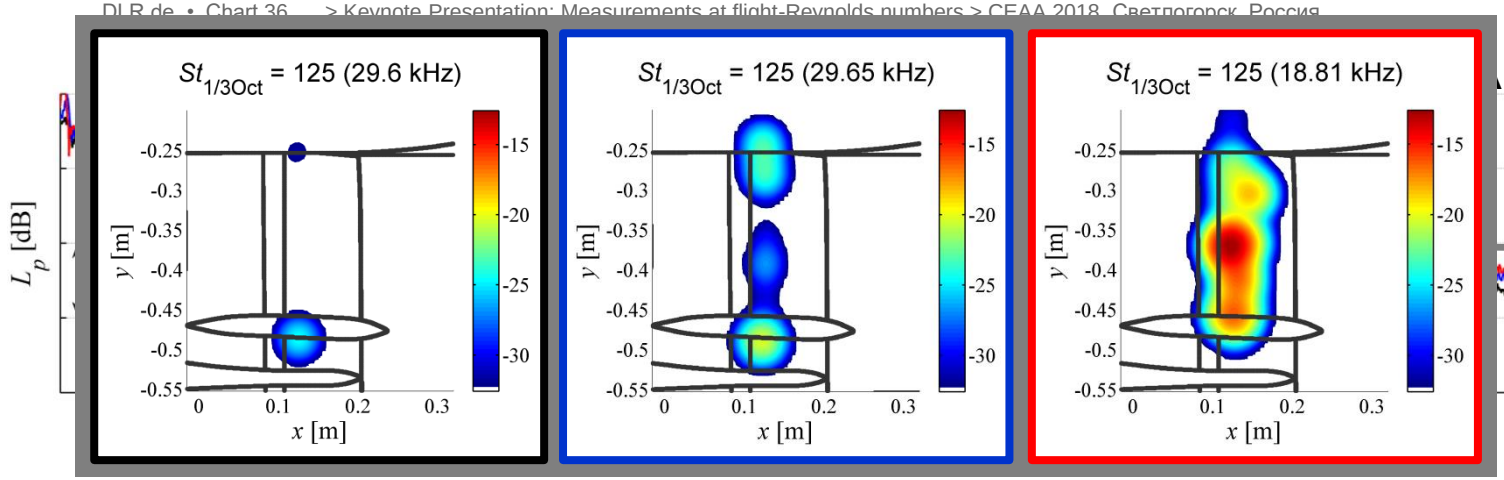


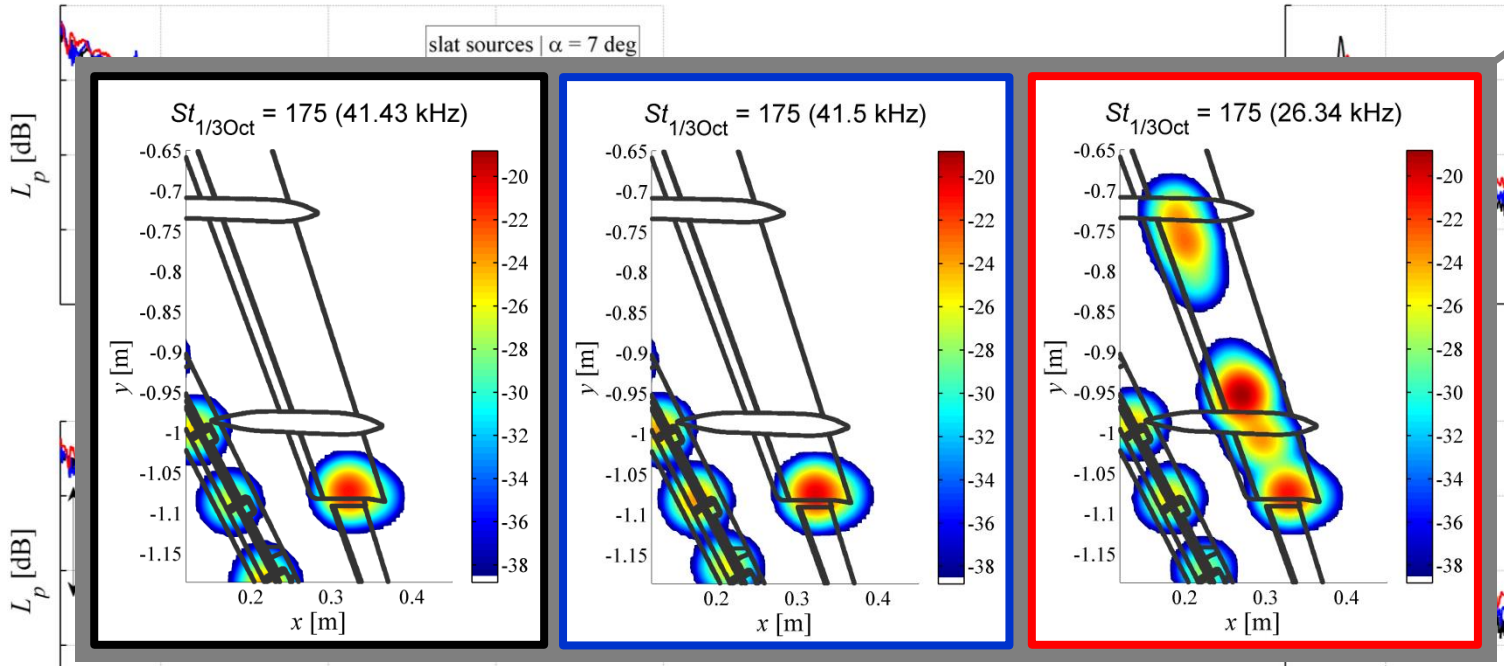




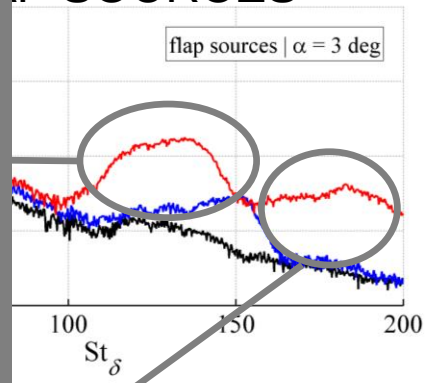


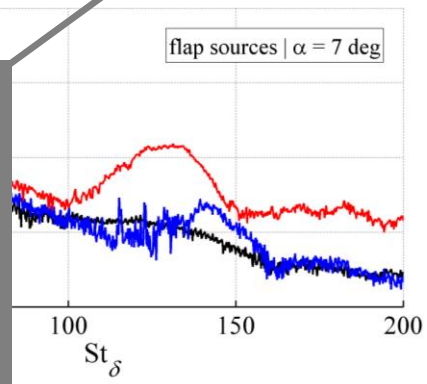
AP SOURCES

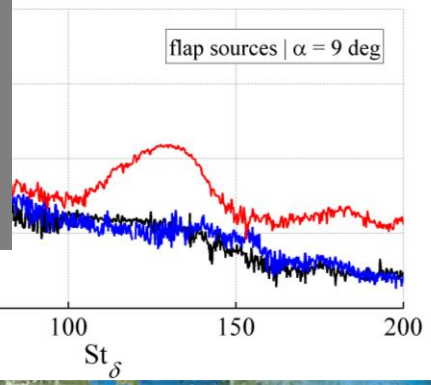

$St_{1/3Oct}$ = 125 (29.6 kHz)
$St_{1/3Oct}$ = 125 (29.65 kHz)
$St_{1/3Oct}$ = 125 (18.81 kHz)
y [m]
x [m]

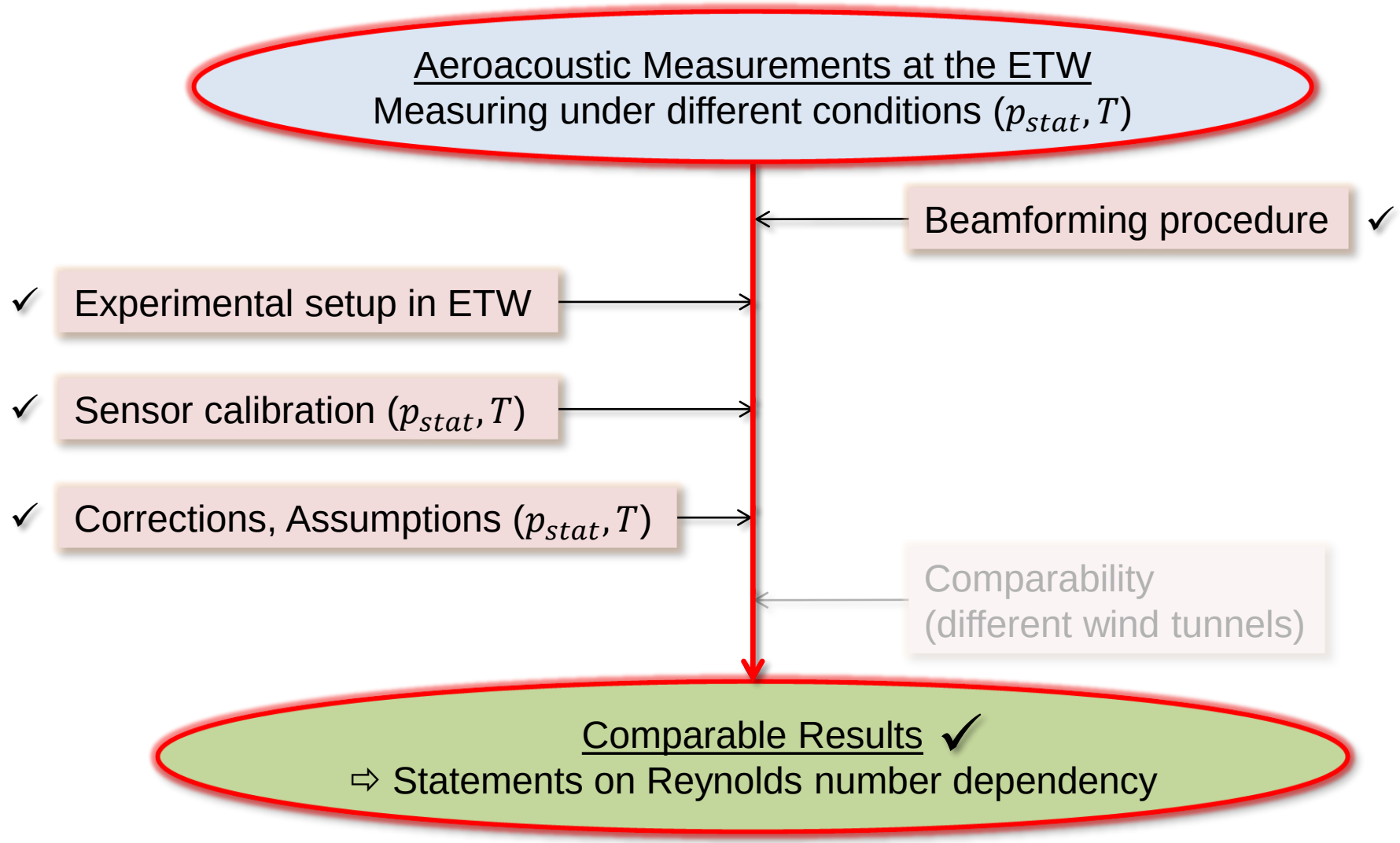

$St_{1/3Oct}$ = 175 (41.43 kHz)
$St_{1/3Oct}$ = 175 (41.5 kHz)
$St_{1/3Oct}$ = 175 (26.34 kHz)
y [m]
x [m]

slat sources | α = 7 deg
L_p [dB]
St_δ


flap sources | α = 3 deg
St_δ


flap sources | α = 7 deg
St_δ

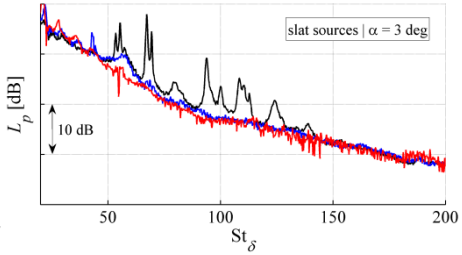

flap sources | α = 9 deg
St_δ

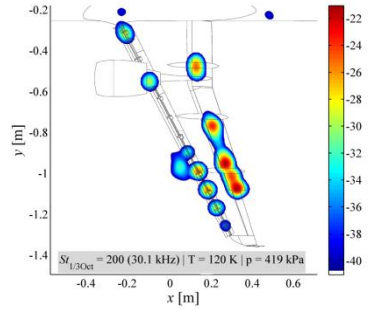

Aeroacoustic Measurements at the ETW
Measuring under different conditions (p_{stat}, T)
Beamforming procedure ✓
✓ Experimental setup in ETW
✓ Sensor calibration (p_{stat}, T)
✓ Corrections, Assumptions (p_{stat}, T)
Comparability
(different wind tunnels)
Comparable Results ✓
⇨ Statements on Reynolds number dependency

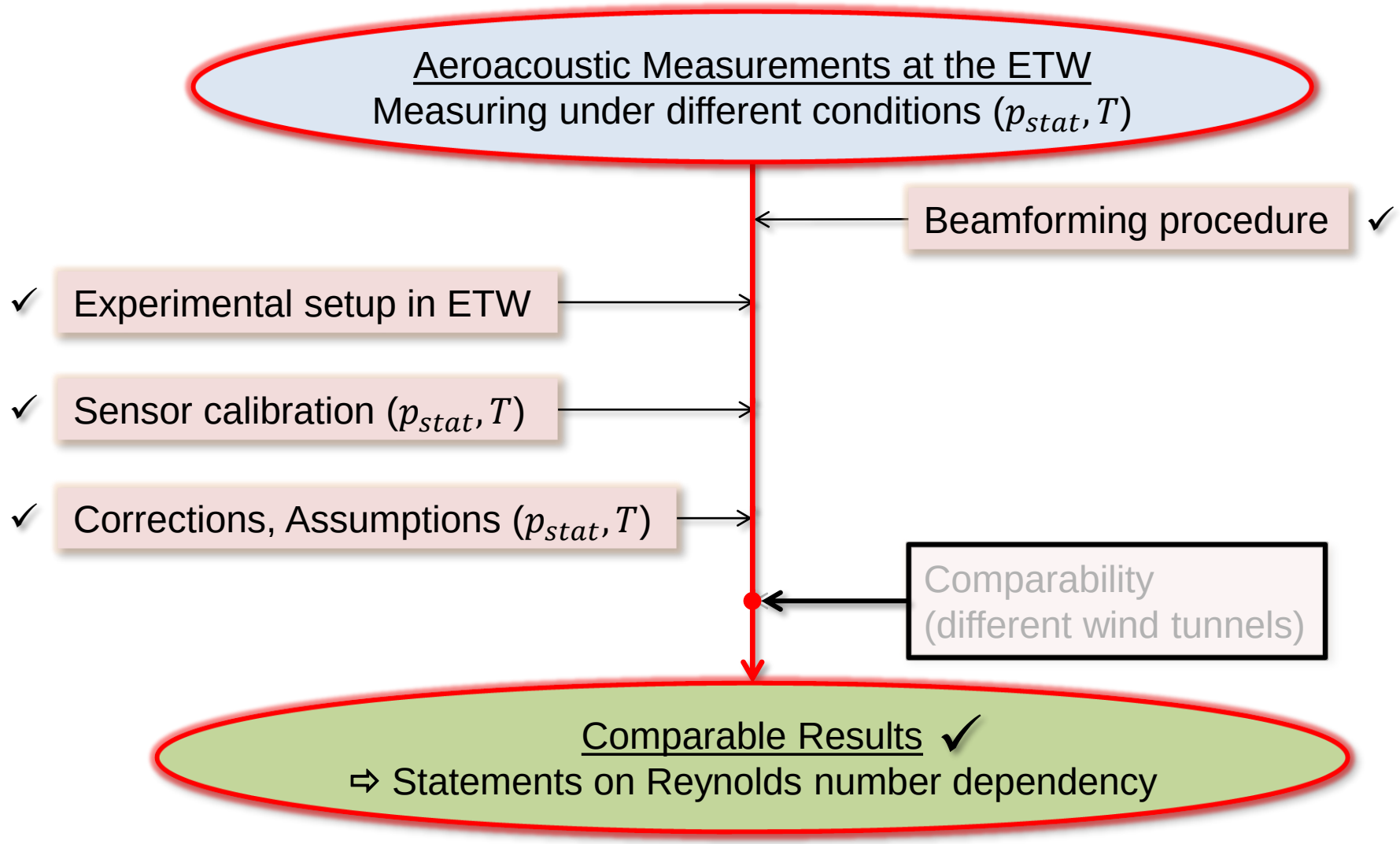
Summary

- Small-scale model airframe noise data at real-flight Reynolds numbers

- Significant Reynolds number dependencies
  - $St_\delta < 100$ ($f_{full-scale} < 1{,}8\ kHz$):
    - Slat tones at low *Re*
    - Various peaks with combined *Re* & *St* dependency
  - $St_\delta > 100$ ($f_{full-scale} < 1{,}8\ kHz$):
    - Inboard slat sources at mid-level *Re*
    - Dominant broadband peaks on flap at real-flight *Re*






Aeroacoustic Measurements at the ETW
Measuring under different conditions (p_{stat}, T)
Beamforming procedure ✓
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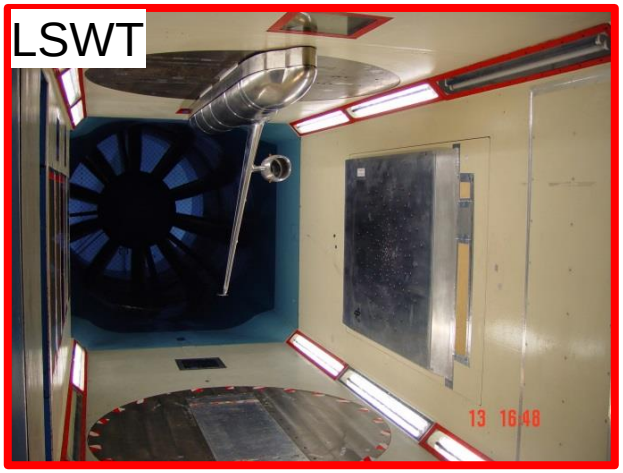
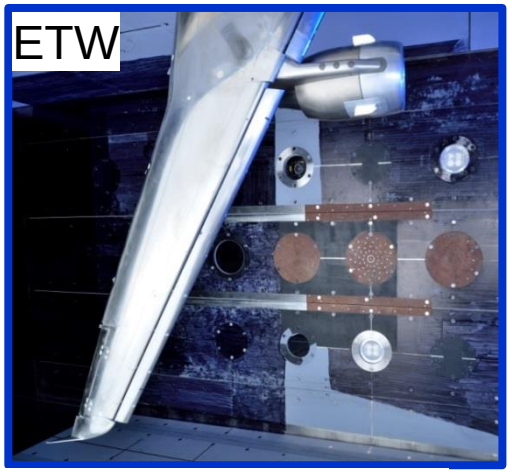
✓ Corrections, Assumptions (p_{stat}, T)
Comparability
(different wind tunnels)
Comparable Results ✓
⇨ Statements on Reynolds number dependency

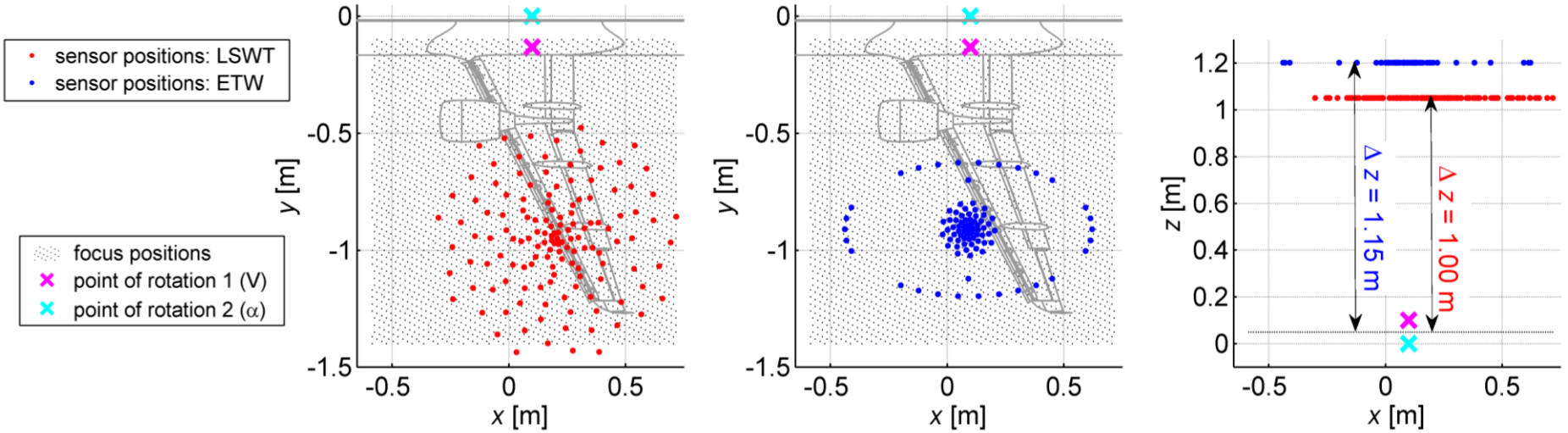
Comparability – Setup



- Identical model
- Identical configuration
- Identical flow parameter (Low Reynolds number)

- Different wind tunnels
- Different microphone arrays
- Different microphones

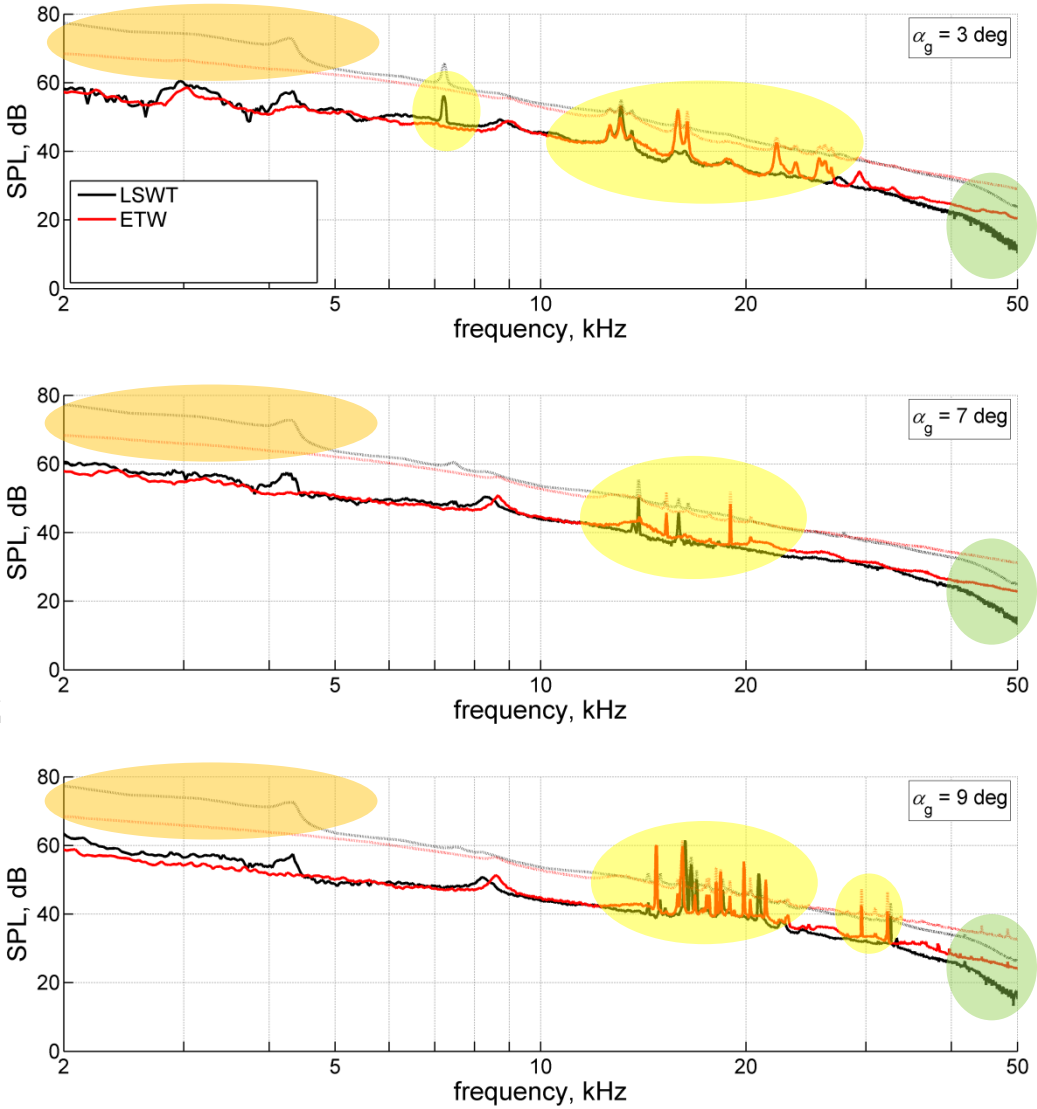




Spehr C. and Ahlefeldt T., "Comparison of Microphone Array Measurements in the Closed Test Section of LSWT and ETW", *CEAS Journal*, accepted for publication (2018).

Comparability – spectra

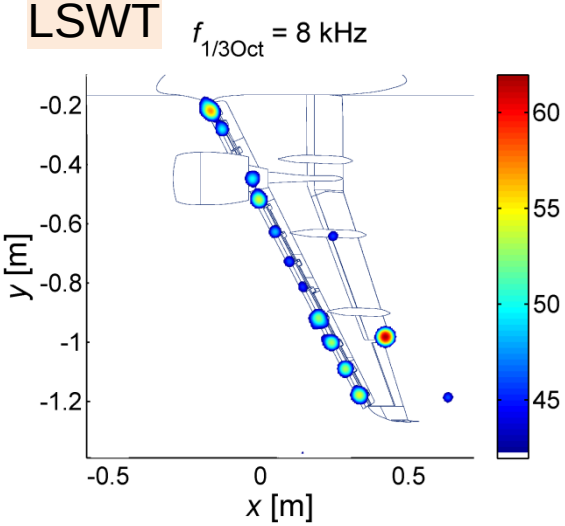
- Overall spectra similar: $\pm 2dB$
- Increased Background noise at LSWT $\Rightarrow$ peak at ≈ 3.2 kHz
- Differences for tonal components (“slat tones”)
- Differences at frequencies > 40 kHz $\Rightarrow$ microphone calibration

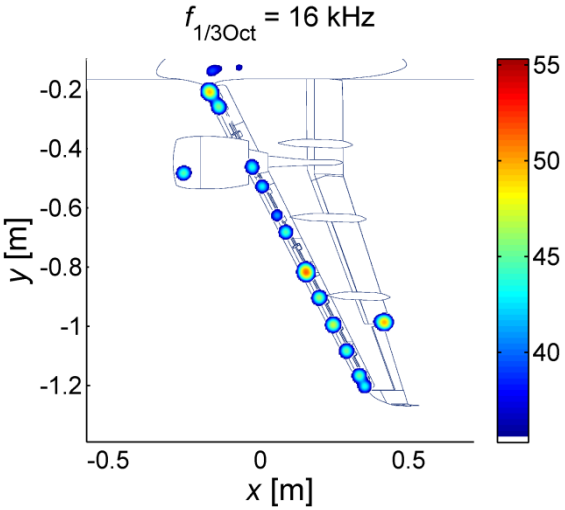


Spehr C. and Ahlefeldt T., “Comparison of Microphone Array Measurements in the Closed Test Section of LSWT and ETW”, *CEAS Journal*, accepted for publication (2018).

Comparability – source maps

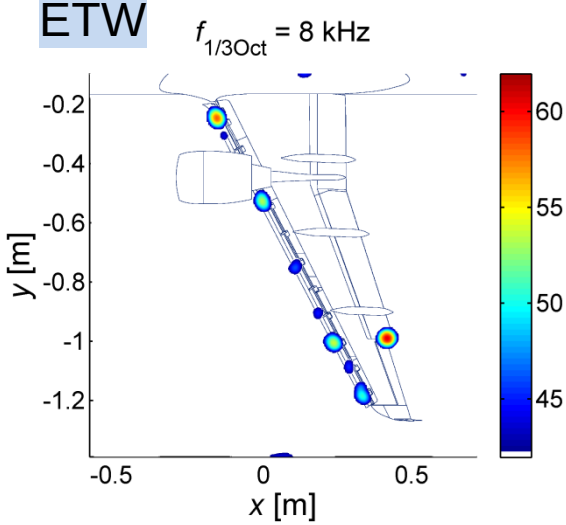
LSWT

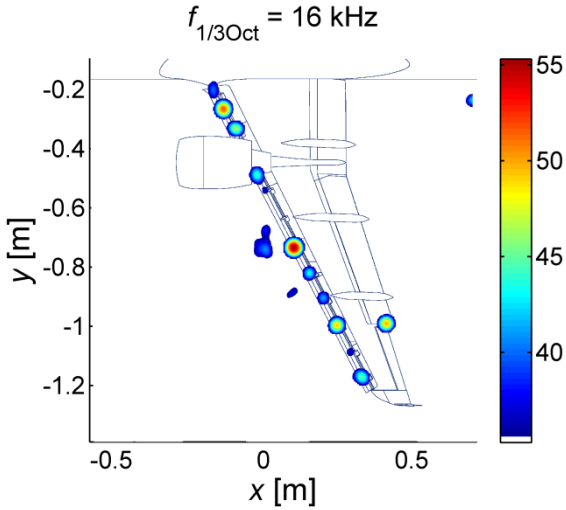


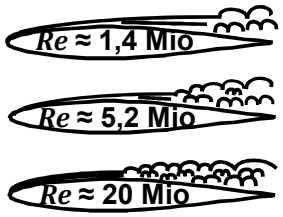


- Main sources are at same positions with minor differences in level
- Sources on slat vary significantly

ETW







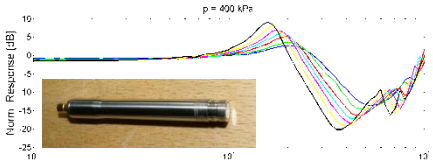
Aeroacoustic Measurements at the ETW
Measuring under different conditions (p_{stat}, T)

Beamforming procedure

$$\boldsymbol{B}(\boldsymbol{y},\omega) = \frac{\boldsymbol{g}(\boldsymbol{y},\omega)^{*}\boldsymbol{C}(\omega)\boldsymbol{g}(\boldsymbol{y},\omega)}{\|\boldsymbol{g}(\boldsymbol{y},\omega)\boldsymbol{g}(\boldsymbol{y},\omega)^{*}\|_{\boldsymbol{F}}^{2}}$$

Experimental setup in ETW

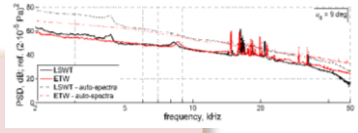
Sensor calibration (p_{stat}, T)



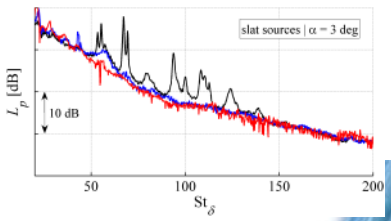
Corrections, Assumptions (p_{stat}, T)

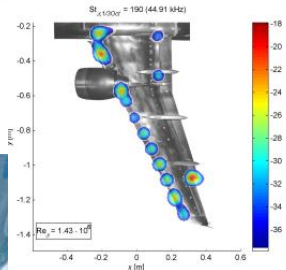
$$\Delta dB = 20log_{10}\left(\frac{\rho c^2}{\rho_0 c_0^2}\right)$$

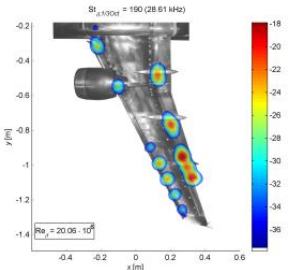
Comparability (different wind tunnels)

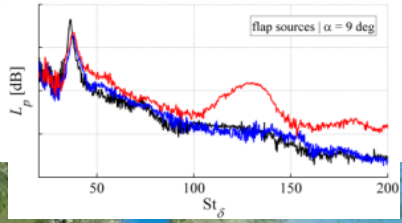


Comparable Results
⇨ Statements on Reynolds number dependency









Take aways

- How do microphone array measurements in WT work
- Corrections and assumptions
- Offer: Sharing data, results and knowledge for cooperation

Questions?

Comments?

thomas.ahlefeldt@dlr.de

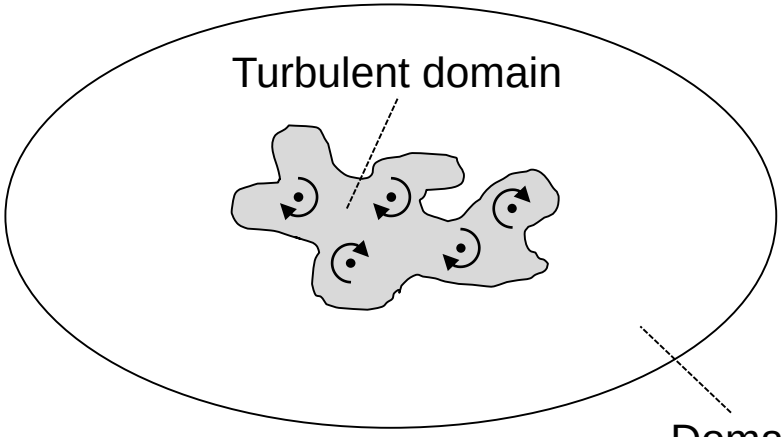
Background: acoustic sources in beamforming

Numerical approach

$$\frac{1}{c^2}\frac{\partial}{\partial t^2}p' - \Delta p' = \sum_{i,j=1}^{3}\frac{\partial^2}{\partial x_i \partial x_j}\left(\rho v_i v_j - \tau_{ij}\right) + \frac{\partial^2}{\partial t^2}\left(\frac{1}{c^2}p' - \rho'\right)$$

Lighthill equation with fluctuating pressure $p' = p - p_0$

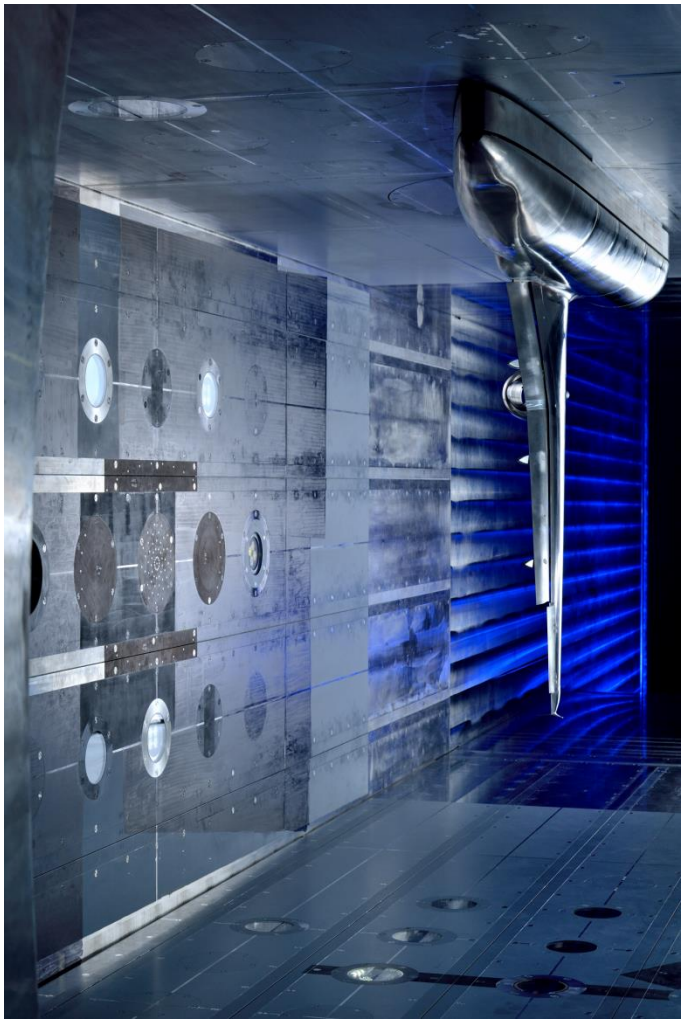
„Equivalent sources“
(contains also kinematic effects: refraction, convection…)



Setup

Airbus K3DY half-model

- Scale: 1:13.6 (7.35%)
- High-lift configuration identical to EWA-Benchmark test 2007 at LSWT

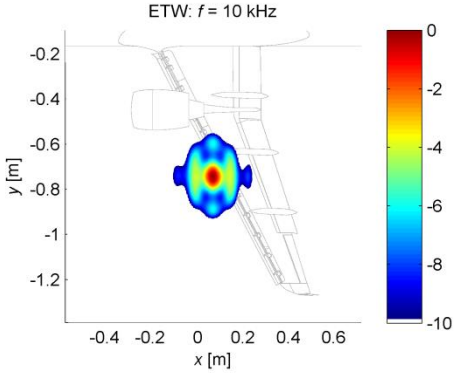


Data points ($M = 0.203$)

	T [K]	p_{stat} [kPa]	Re_δ [10^6]	q/E [10^{-8}]
DP I	310	110	1.42	1.57
DP II	125	115	5.16	1.57
DP III	310	399	5.16	5.70
DP IV	120	419	20.00	5.70

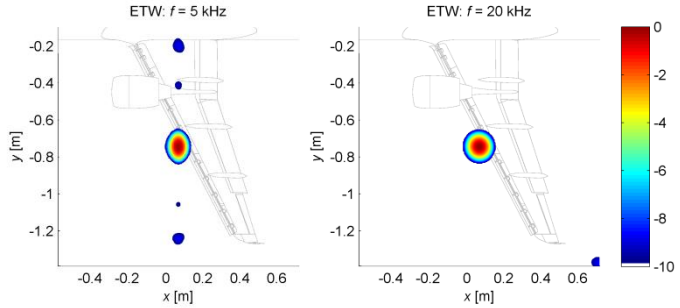
Ahlefeldt T., “Aeroacoustic Measurements of a Scaled Half-Model at High Reynolds Numbers”, *AIAA Journal*, Vol. 55, No. 1 (2017).

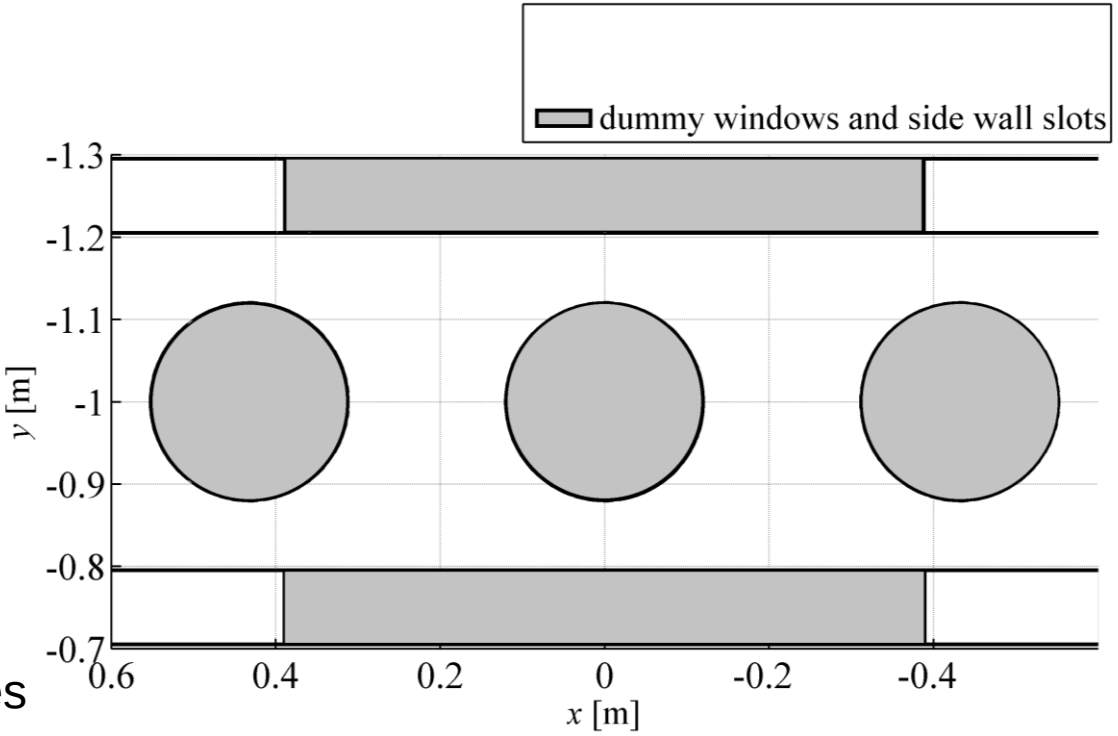
Setup



- Limited positioning of microphones:
  - Significantly restricted angle/area of observation
  - Conventional beamforming: strong sidelobes

- Different microphone groups used for conventional maps (“nested arrays”)

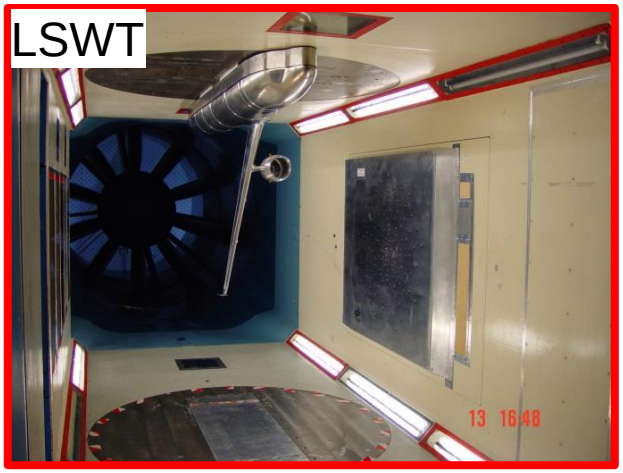




- After validation:
  *CLEAN-SC with all microphones

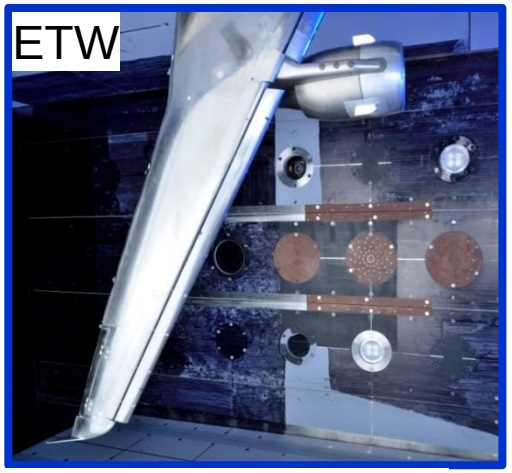
*Sijtsma P., “CLEAN based on spatial source coherence”, *International Journal of Aeroacoustics*, Vol 6, 2012.

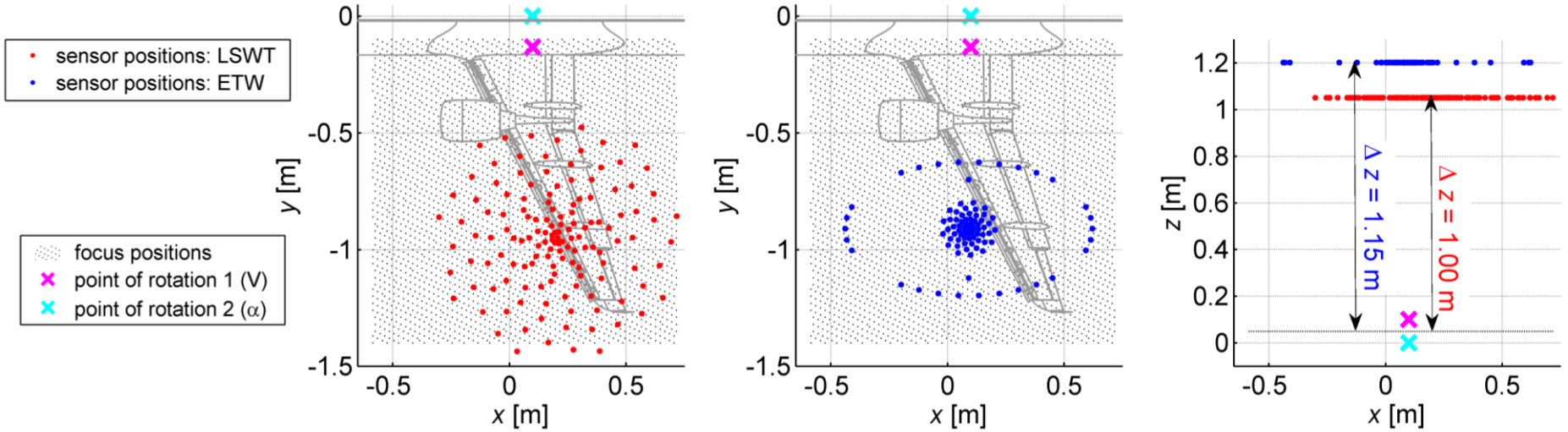
Comparability – Setup



- Identical model
- Identical configuration
- Identical flow parameter (Low Reynolds number)

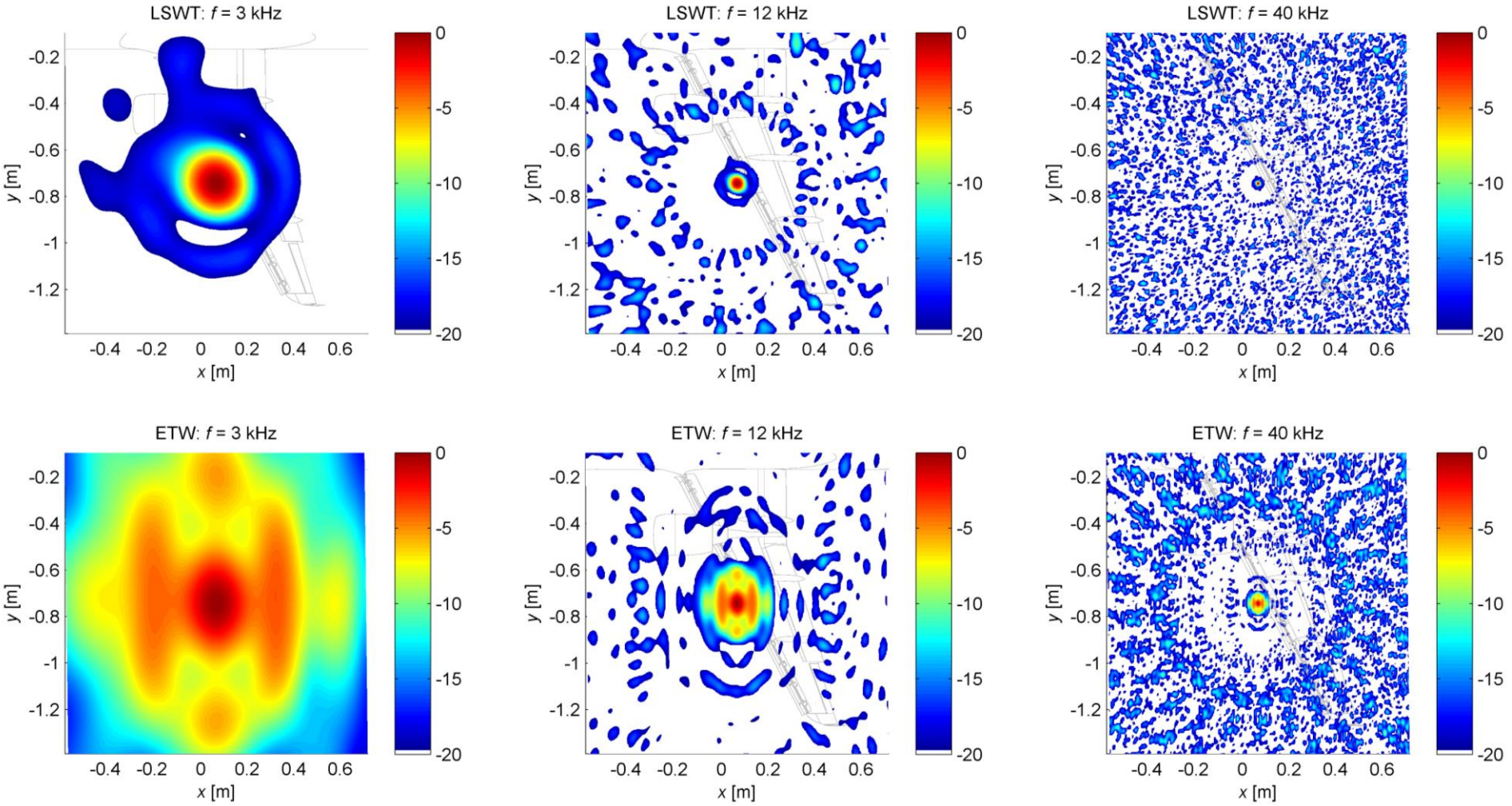
- Different wind tunnels (but similar dimensions)
- Different microphone arrays





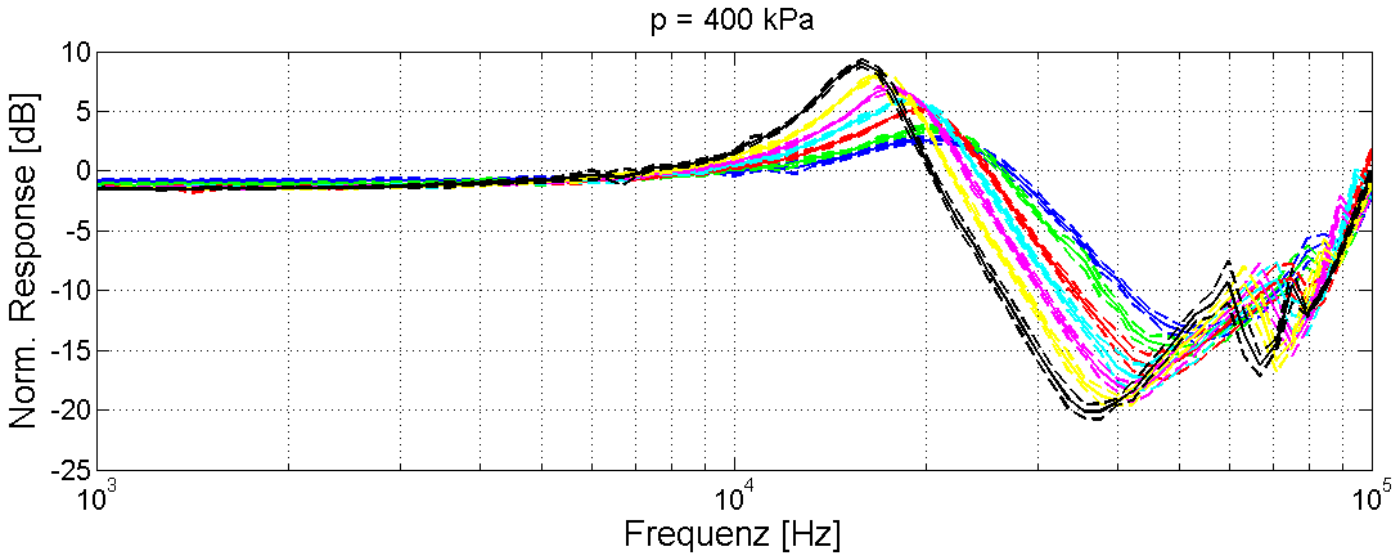
Spehr C. and Ahlefeldt T., "Comparison of Microphone Array Measurements in the Closed Test Section of LSWT and ETW", *CEAS Journal*, accepted for publication (2018).

Comparability – PSF



Sensor calibration – amplitude response

$$p_{stat} = 400\ \text{kPa}$$
$$120\ \text{K} \leq T \leq 290\ \text{K}$$

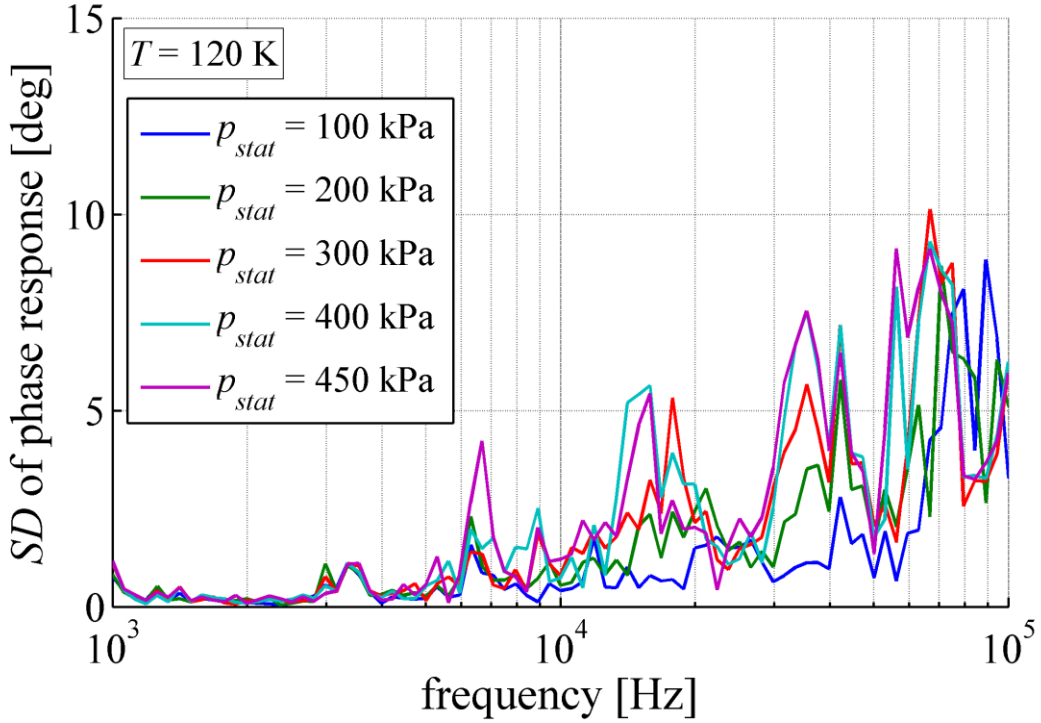


With standard deviation

Sensor calibration – phase response

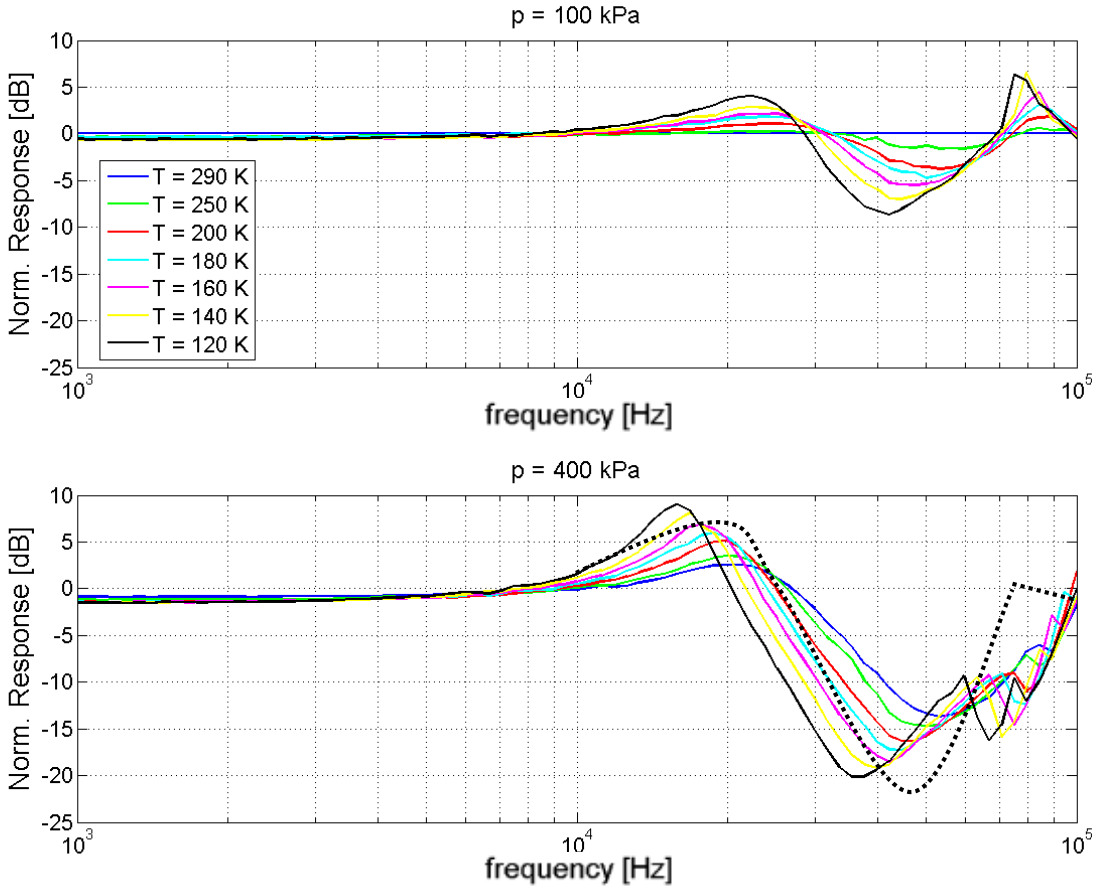
$$\boldsymbol{T = 120\ K}$$
$$\boldsymbol{100\ \text{kPa} \leq p_{stat} \leq 400\ \text{kPa}}$$

- Standard deviation up to 10 deg
- ≈ commercially used array microphones
- Influence on beamforming result < 0.05 dB

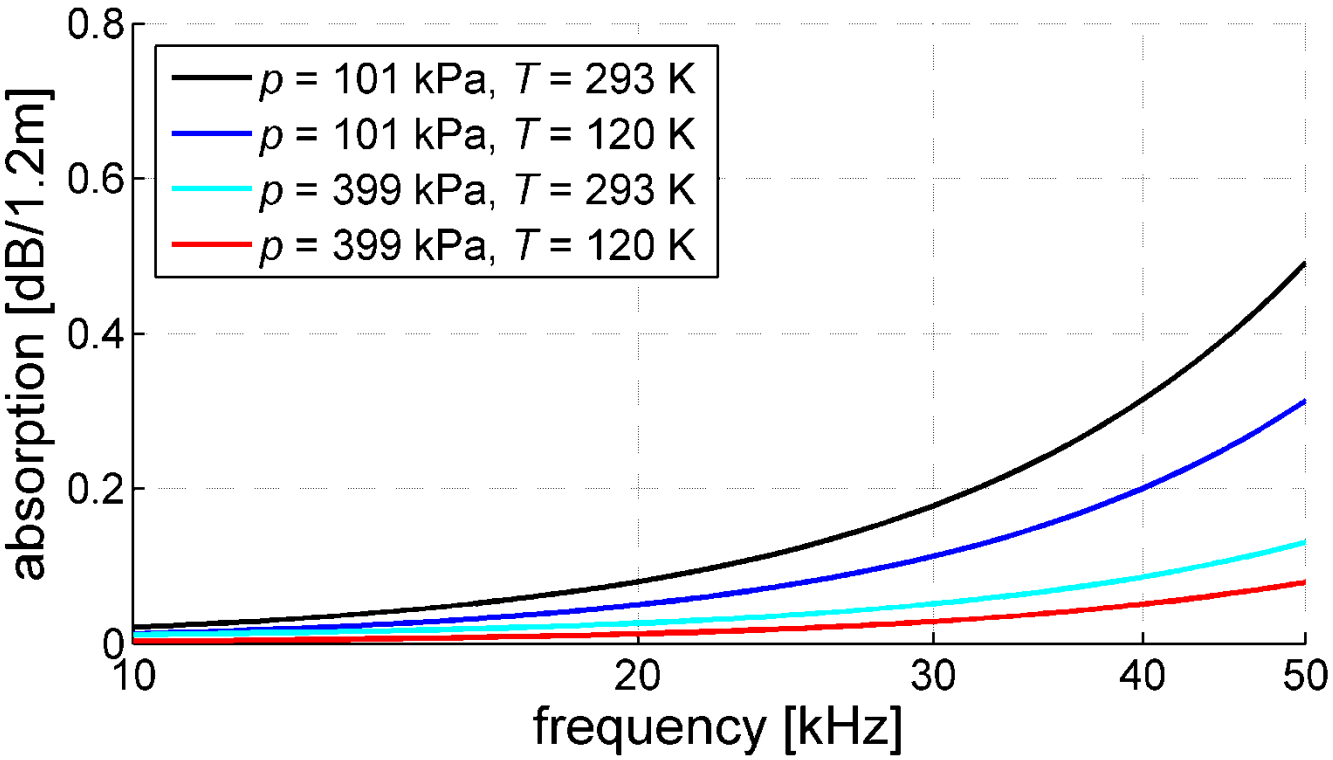


Ahlefeldt T., “Aeroacoustic Measurements of a Scaled Half-Model at High Reynolds Numbers”, *AIAA Journal*, Vol. 55, No. 1 (2017).

Sensor calibration



Atmospheric absorption



- Shields, F. D.; Bass, H. E. “Atmospheric absorption of high frequency noise and application to fractional-octave bands” NASA CR-2760, 1977

$$M = {}^{u}/_{c}$$

$$St = {}^{fD}/_{u}$$

$$He = {}^{2\pi fD}/_{c}$$

Assumptions / Corrections

- Aeroacoustic similarity:
  Reynolds number, Mach number, Strouhal number, (Helmholtz number)

Test section environment
Static pressure p_{stat}
Temperature T

$$M = {}^{u}/_{c}$$
$$St = {}^{fD}/_{u}$$
$$He = {}^{2\pi fD}/_{c}$$

Assumptions / Corrections

- Aeroacoustic similarity:
  Reynolds number, Mach number, Strouhal number, (Helmholtz number)

Test section environment	Changing properties	$M = \frac{u}{c} = const.$
Static pressure p_{stat}	Reynolds number	Reynolds number
	density ρ	density ρ
Temperature T	speed of sound c	speed of sound c
	Young's modulus E	⇨ flow speed u ⇨ elastic deformation q/E

Source mechanisms: $p = function(frequency, amplitude, Reynolds\ number)$

c, u ⇨ St, He $\quad$ ρ, c, u

Results – Source maps (CLEAN-SC)

M = 0.203 | α = 3° | Variation of Strouhal number

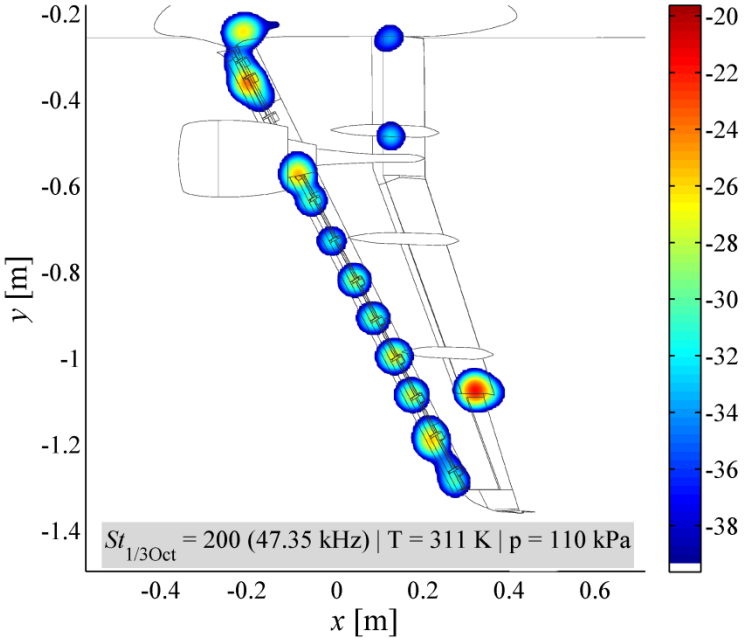
- Different Reynolds number
- **7%** to **26%** of real-flight Re_δ
- Same deformation

$\boldsymbol{Re_\delta = 1.42 \cdot 10^6}$	$\boldsymbol{Re_\delta = 5.16 \cdot 10^6}$
$q/E = 1.57 \cdot 10^{-8}$	$q/E = 1.57 \cdot 10^{-8}$

Results – Source maps (CLEAN-SC)

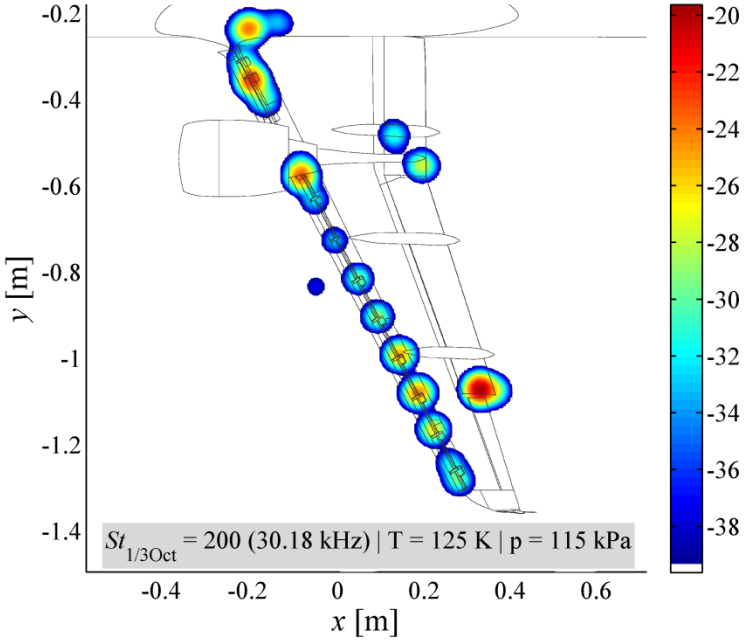
M = 0.203 | α = 3° | Variation of Strouhal number

$St_{1/3Oct} = 200 \;|\; f_{full-scale} = 47.35$ kHz



$Re_\delta = 1.42 \cdot 10^6$

$q/E = 1.57 \cdot 10^{-8}$



$Re_\delta = 5.16 \cdot 10^6$

$q/E = 1.57 \cdot 10^{-8}$

Results – Source maps (CLEAN-SC)

M = 0.203 | α = 3° | Variation of Strouhal number

- Same Reynolds number
- **26%** of real-flight Re_δ
- Different deformation

$\boldsymbol{Re_\delta = 5.16 \cdot 10^6}$

$q/E = 1.57 \cdot 10^{-8}$

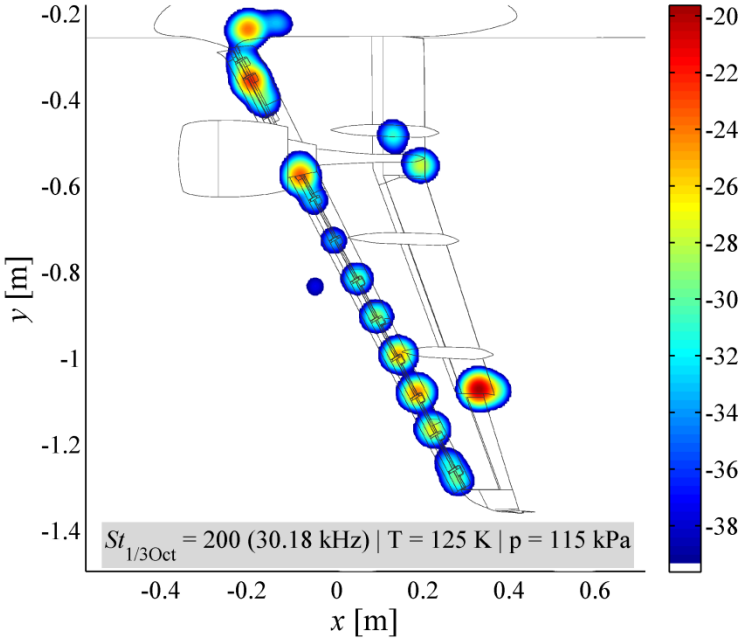
$\boldsymbol{Re_\delta = 5.16 \cdot 10^6}$

$q/E = 5.70 \cdot 10^{-8}$

Results – Source maps (CLEAN-SC)

M = 0.203 | α = 3° | Variation of Strouhal number

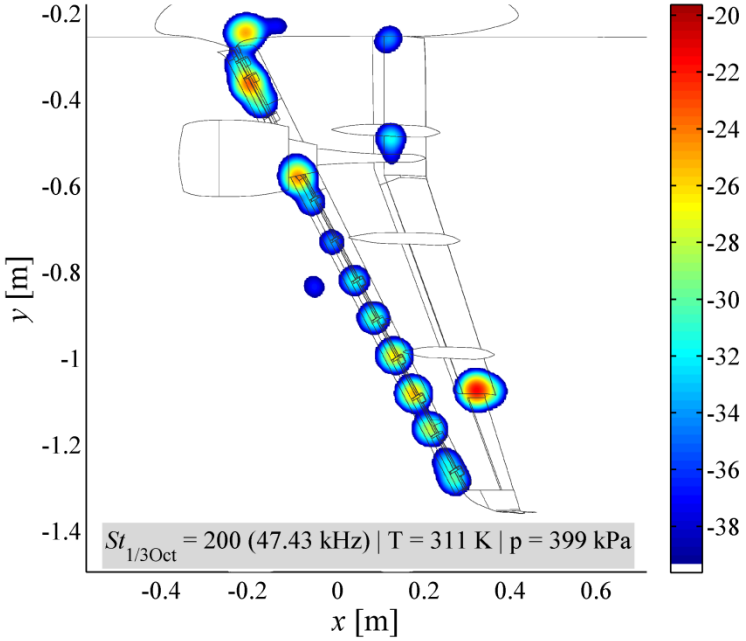
$St_{\delta,1/3Oct} = 200 \;|\; f_{full-scale} = 30.18$ kHz



$Re_\delta = 5.16 \cdot 10^6$

$q/E = 1.57 \cdot 10^{-8}$

$St_{\delta,1/3Oct} = 200 \;|\; f_{full-scale} = 47.43$ kHz



$Re_\delta = 5.16 \cdot 10^6$

$q/E = 5.70 \cdot 10^{-8}$

Results – Source maps (CLEAN-SC)

M = 0.203 | α = 3° | Variation of Strouhal number

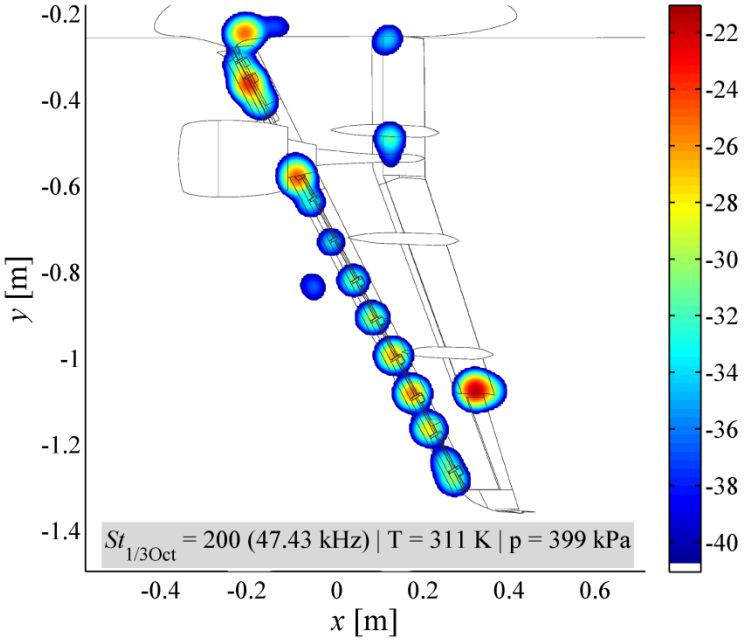
- Different Reynolds number
- **26%** to **100%** of real-flight Re_δ
- Same deformation

$Re_\delta = 5.16 \cdot 10^6$	$Re_\delta = 20.0 \cdot 10^6$
$q/E = 5.70 \cdot 10^{-8}$	$q/E = 5.70 \cdot 10^{-8}$

Results – Source maps (CLEAN-SC)

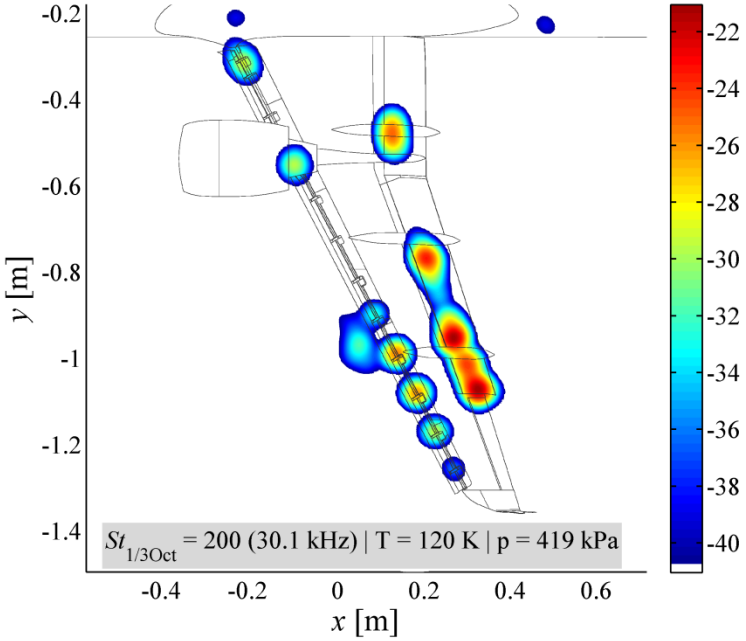
M = 0.203 | α = 3° | Variation of Strouhal number

$St_{\delta,1/3Oct} = 2.00 \parallel f_{full-scale} = 33.5\ kHz$



$Re_\delta = 5.16 \cdot 10^6$

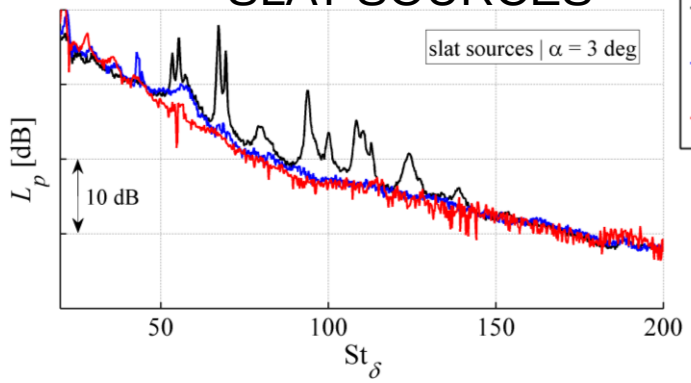
$q/E = 5.70 \cdot 10^{-8}$

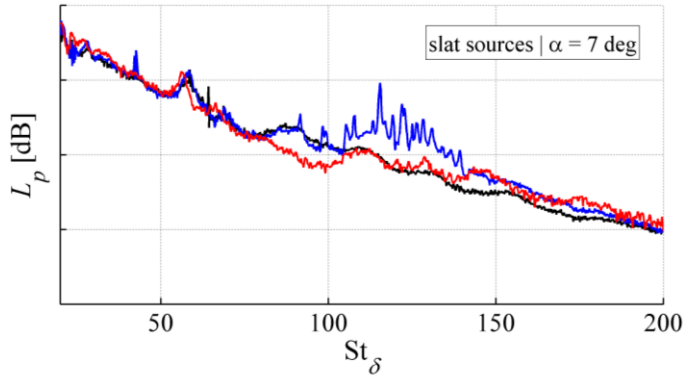


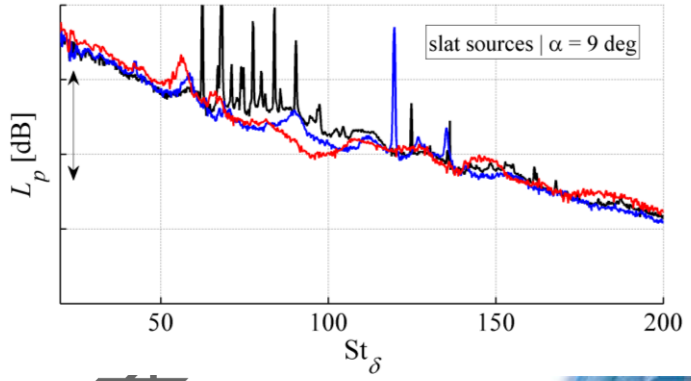
$Re_\delta = 20.0 \cdot 10^6$

$q/E = 5.70 \cdot 10^{-8}$

SLAT SOURCES





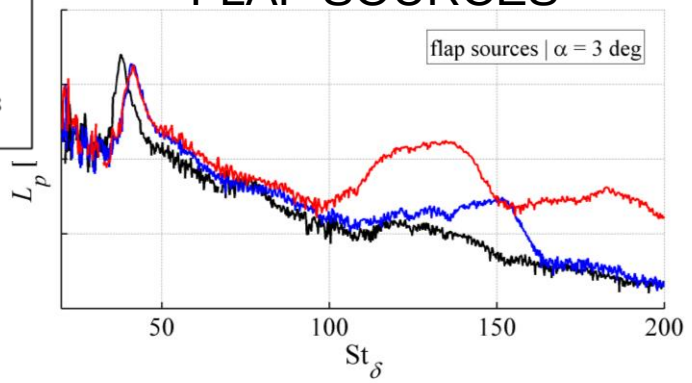


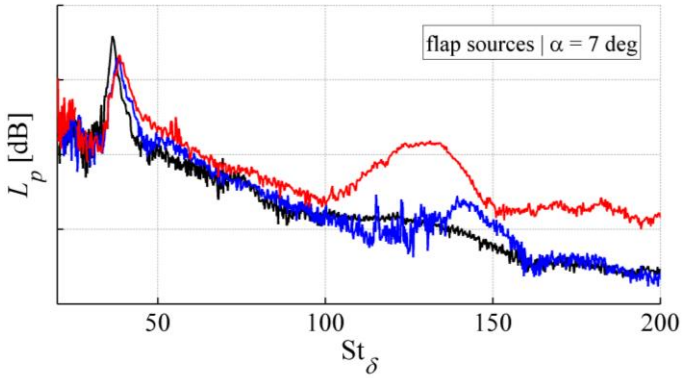
DP I: $Re_\delta = 1.43 \cdot 10^6$ | $q/E = 1.55 \cdot 10^{-8}$

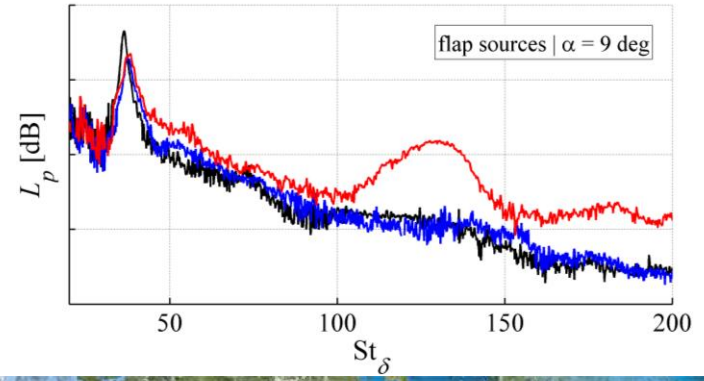
DP III: $Re_\delta = 5.17 \cdot 10^6$ | $q/E = 5.64 \cdot 10^{-8}$

DP IV: $Re_\delta = 20.06 \cdot 10^6$ | $q/E = 5.64 \cdot 10^{-8}$

FLAP SOURCES







Equations

$$\mathrm{Re} = \frac{\rho \cdot u_\infty \cdot d}{\eta} = \frac{\rho \cdot \mathrm{M} \cdot d}{c \cdot \eta}$$

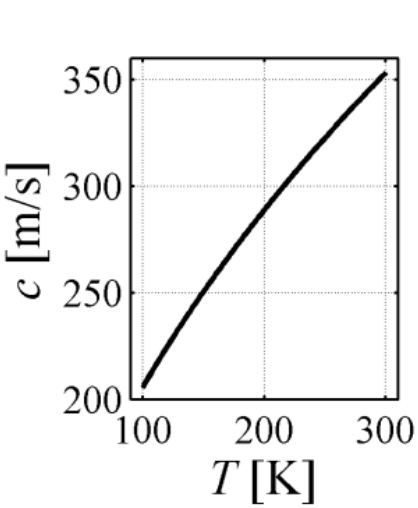
$$\rho = \frac{p}{\mathcal{R}T} \quad \text{(ideal gas)}$$

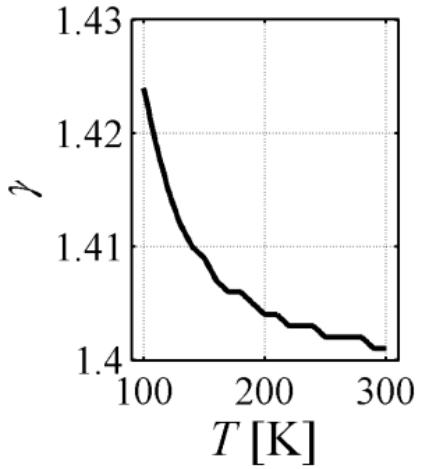
$$M = {}^{u}/_{c}$$

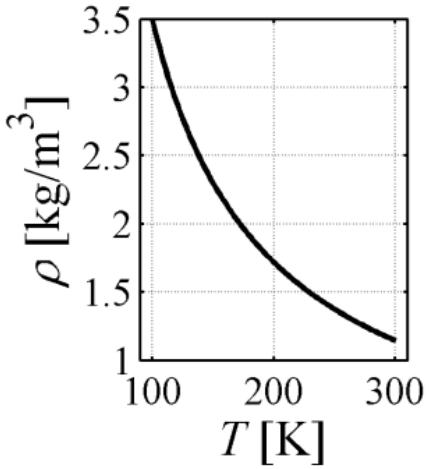
$$St = {}^{fD}/_{u}$$

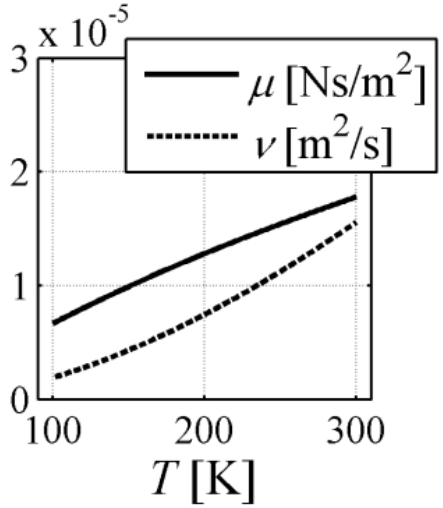
$$He = {}^{2\pi fD}/_{c}$$

$$c = \sqrt{\frac{\gamma(p,T)\mathcal{R}T}{m_{mol}}}$$









Electrostatic Actuator

$$p_{dynamic}[rms] = \frac{\varepsilon \cdot E_0 \cdot e_{rms}}{d^2} \cdot R_{area}$$

where:
- E_0 = applied DC-voltage
- e_{rms} = rms value of applied AC-voltage
- $p_{dynamic}$ = produced dynamic pressure
- d = plate distance
- ε = dielectric constant of the gas between plates

[*Microphone Handbook, Vol.1: Theory*, Brüel&Kjaer, July 1996, BE 1447-11]

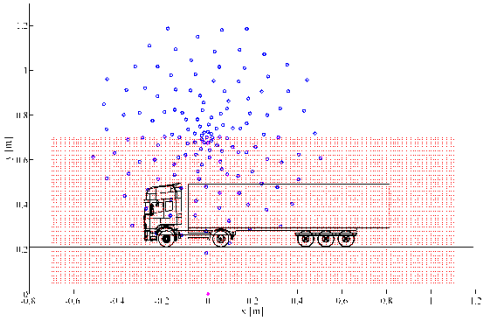
$$\varepsilon = \varepsilon_r \varepsilon_0$$

$$\varepsilon_0 \approx 8.85 \cdot 10^{-12}\ \mathbf{F/m}$$

$$\varepsilon_r(295\ \mathrm{K},\ 1.0\ \mathrm{kPa}) \approx \mathbf{1.0005}$$
$$\varepsilon_r(120\ \mathrm{K},\ 4.5\ \mathrm{kPa}) \approx \mathbf{1.0055}$$

$$\Rightarrow \Delta dB \approx 0.04\ \mathrm{dB}$$

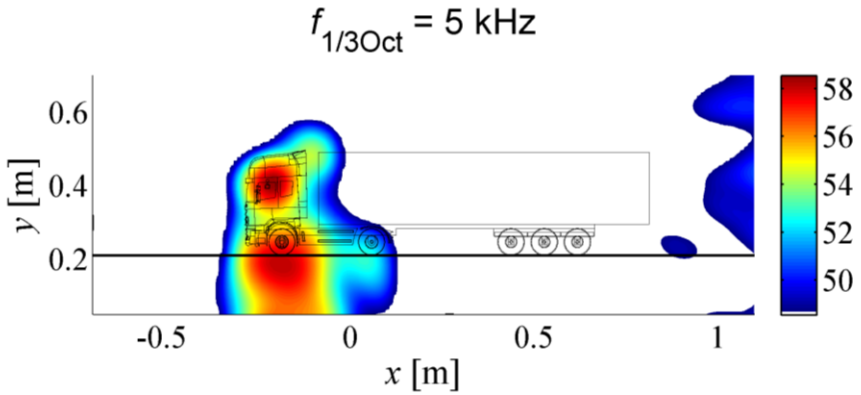
DLR

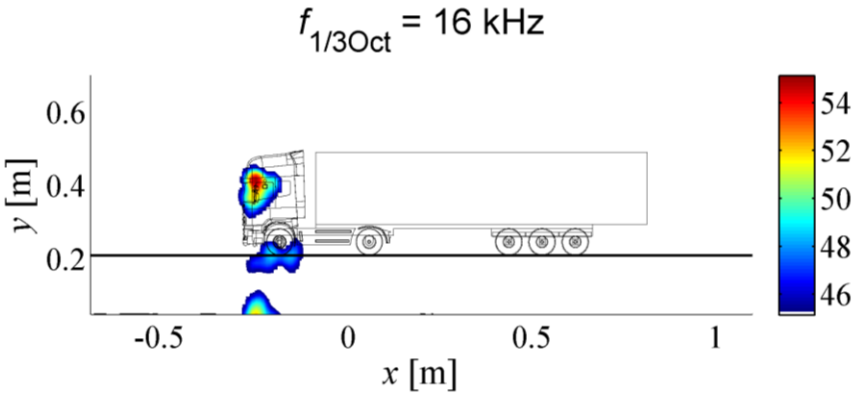


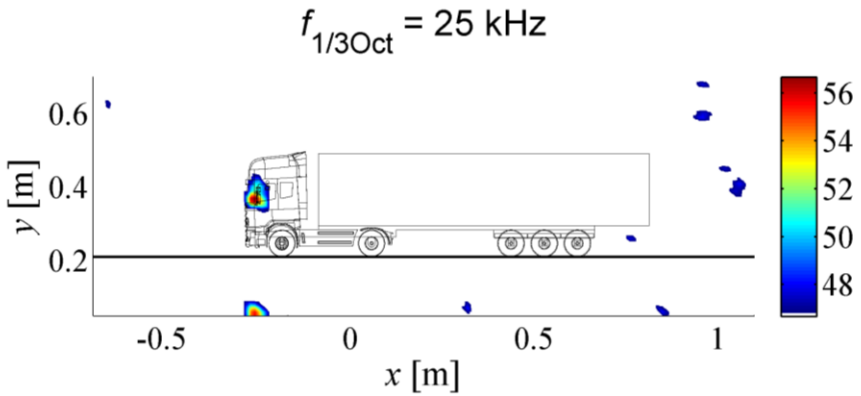
Repeat without disturbing sources

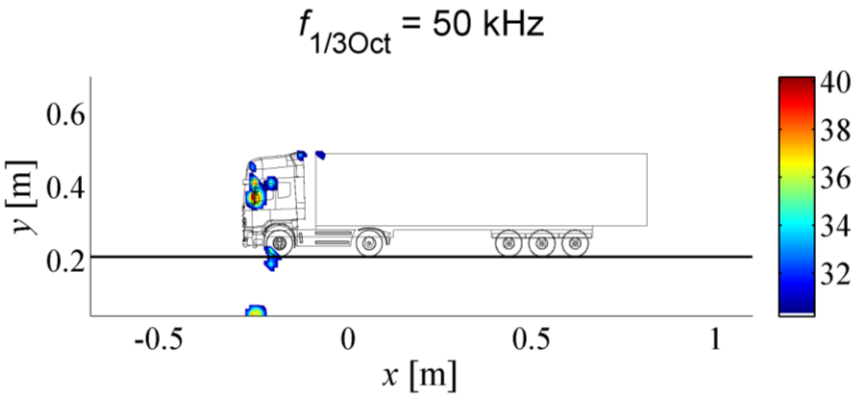
Source map u = 40 m/s; α = 0°

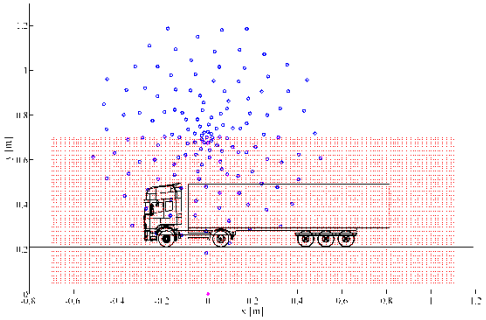
- Overview









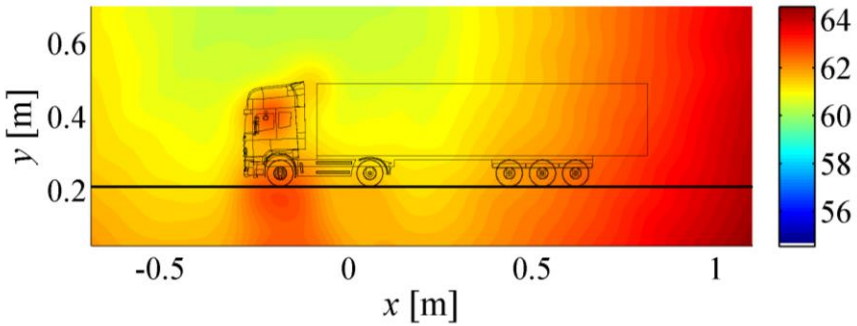


Repeat without disturbing sources

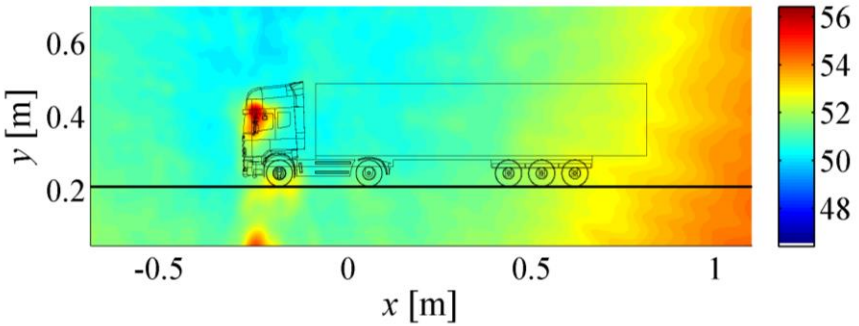
Source map u = 40 m/s; α = 0°

- Comparison: „Diagonal Removal off“

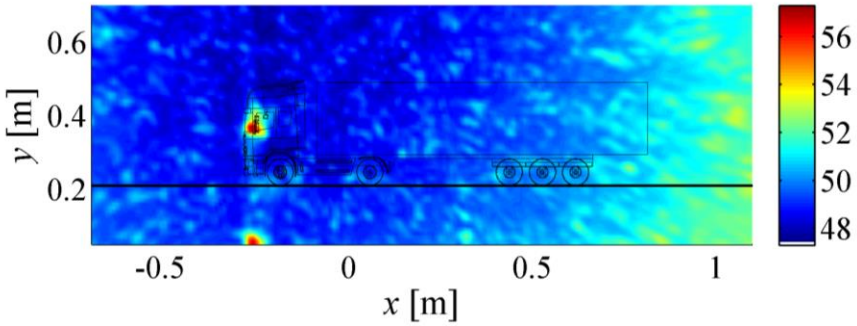
$f_{1/3Oct}$ = 5 kHz



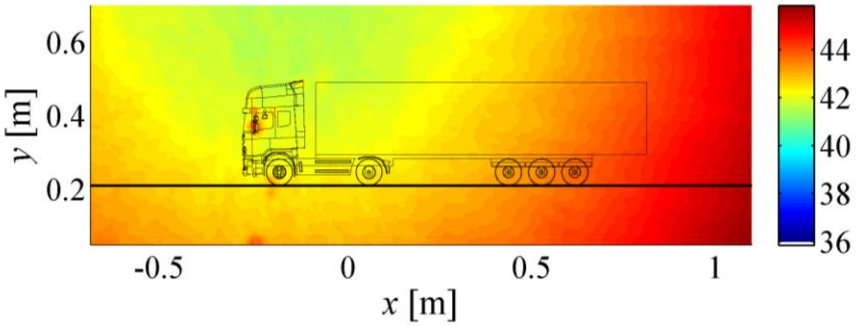
$f_{1/3Oct}$ = 16 kHz



$f_{1/3Oct}$ = 25 kHz



$f_{1/3Oct}$ = 50 kHz



Interpretation of data