MEASUREMENT-INFORMED AURALIZATION FOR A DISTRIBUTED PROPULSION SYSTEM OF AN URBAN AIR MOBILITY VEHICLE

Acoustics of Drones and Urban Air Mobility Vehicles

Stephen Schade, S. Guérin, L. Klähn, K.-S. Rossignol

18th DEGA Symposium

09th September 2025

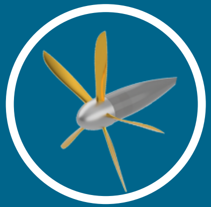
DLR

Agenda

01 Auralization framework

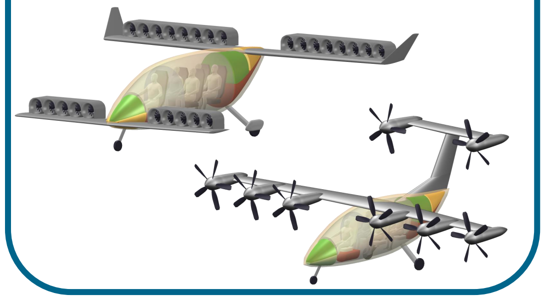
02 Application on distributed, ducted fans

03 Application on distributed propellers

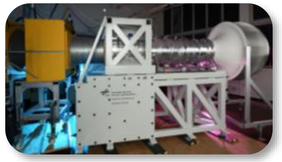


Motivation – Auralization

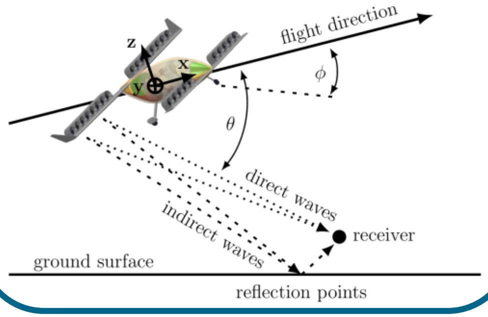
propulsion system



acoustic measurements



auralization



sound perception

- **sound signatures of distributed propulsion systems** still mainly unknown
- **psychoacoustic sound characteristics** impact aural impression
- **auralization as an important tool** to make noise signatures audible early in the development process
- enables a **direct link between psychoacoustic studies and propulsion system design**

Analytical auralization framework

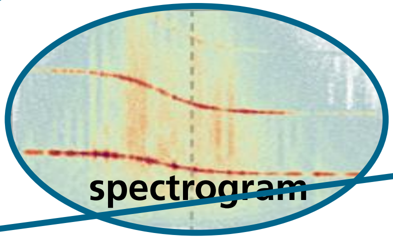
analytical input

RANS-informed noise prediction

PropNoise

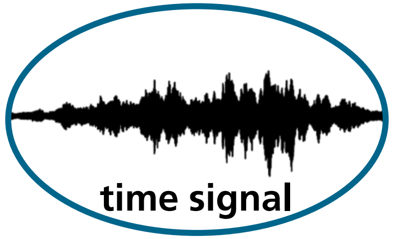
virtual flyover simulation

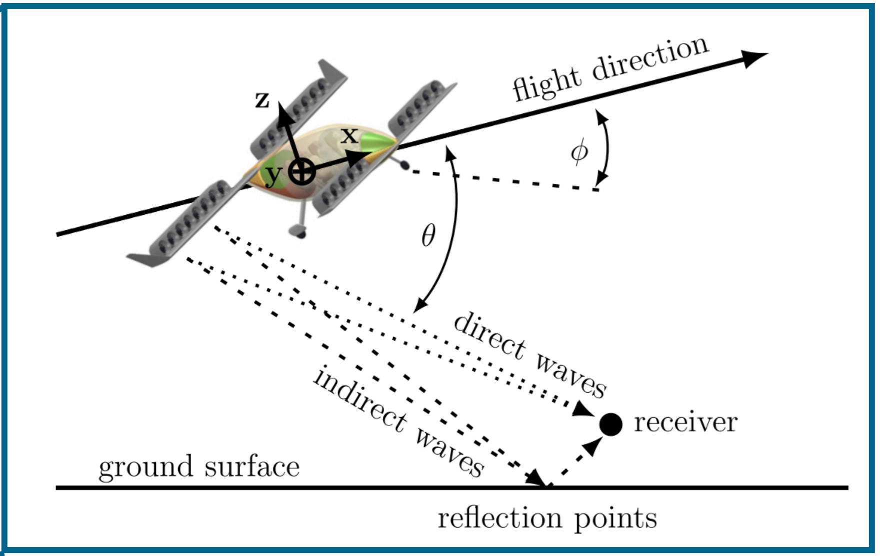
VIOLIN



binaural noise synthesis

CORAL



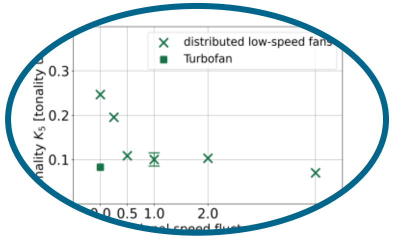


turnaround time < 5Min

post-processing

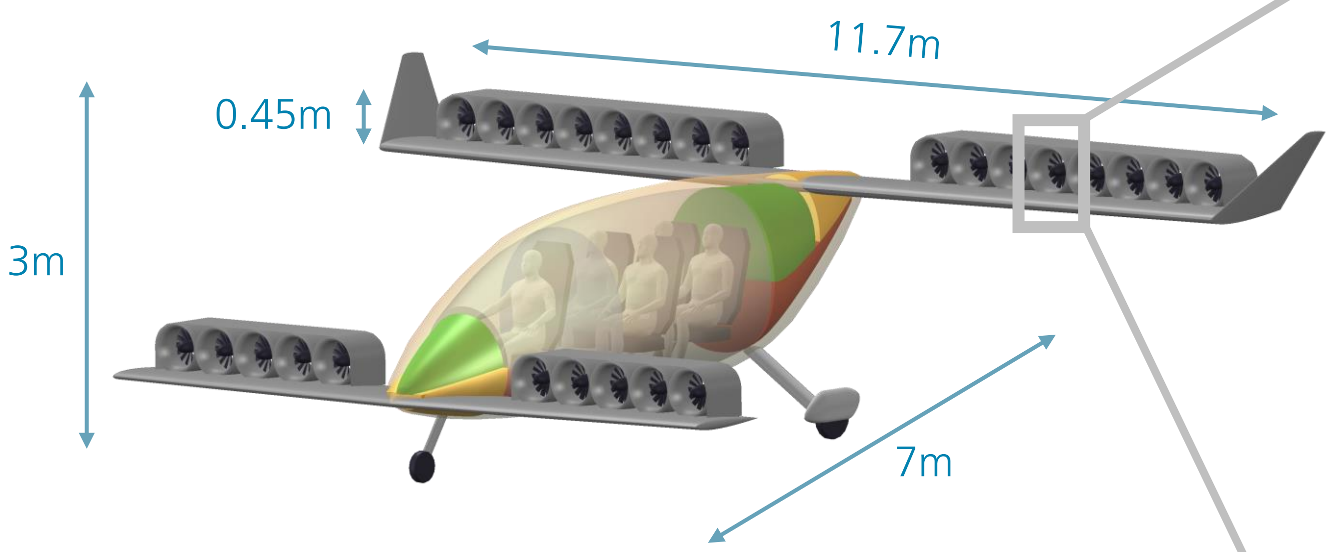
sound quality analysis *

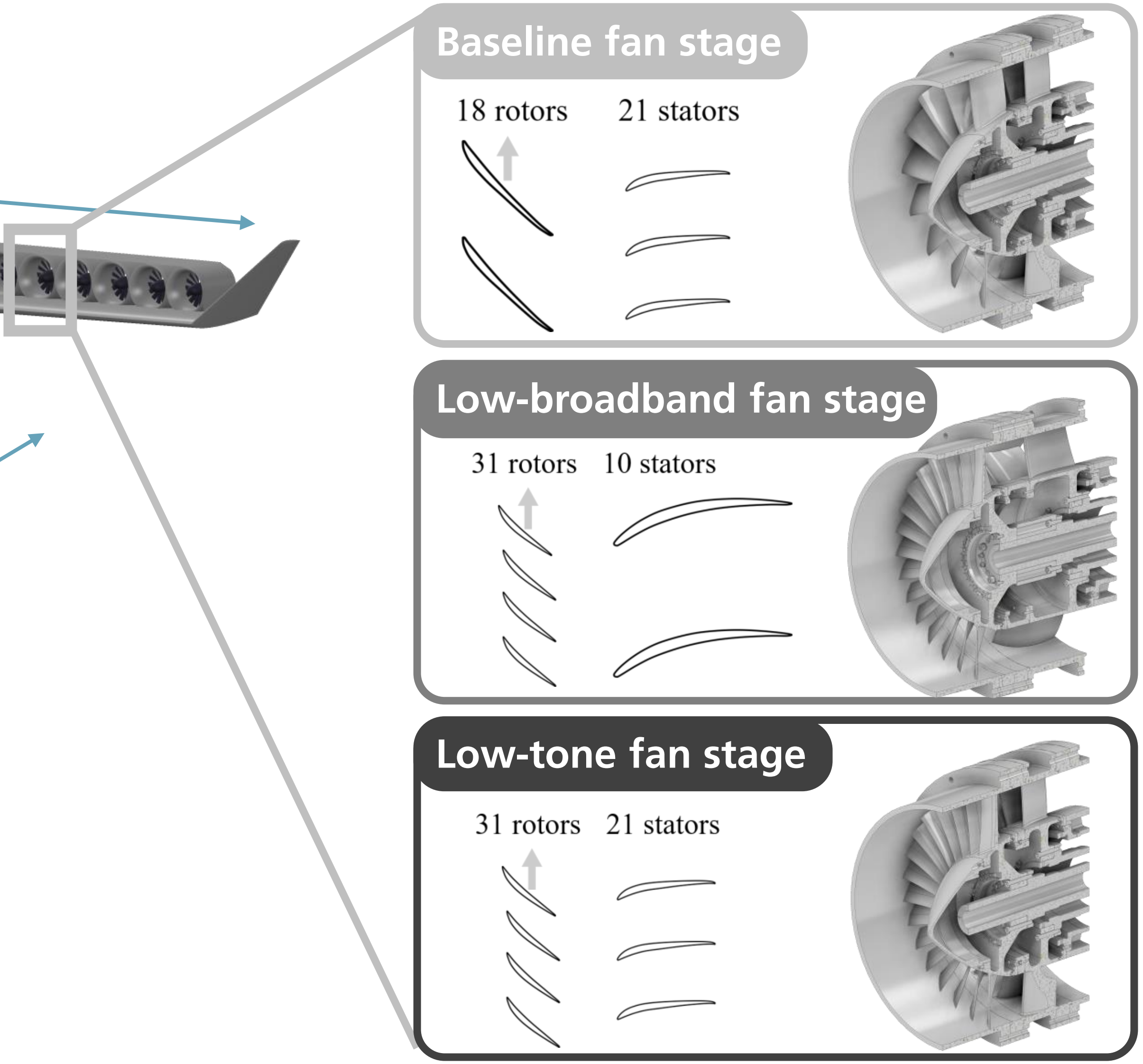
SQAT



*cooperation with TU Delft

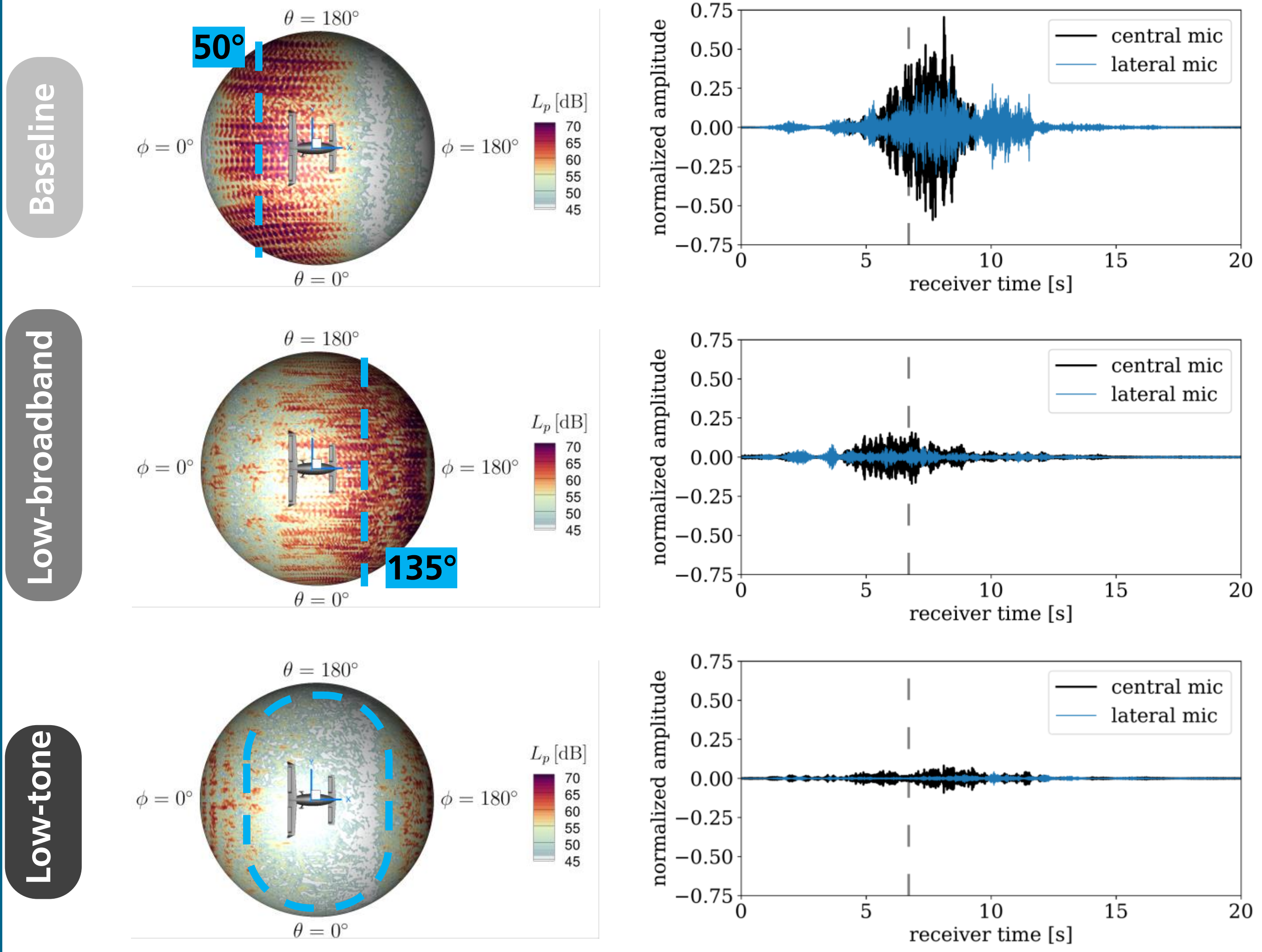
Tilt-duct vehicle and fan design *(project VIRLWINT)*





- Payload of **500 kg**
- Mission length of **150 km**
- Cruise speed of **200 km/h**
- Number of fans **26**

Impact on fan design on sound quality



Schade et al.
JASA 2025

Limitation

Analytical noise prediction?

- The better the prediction of the sound sources, the higher the quality of the auralization result

How do the results change if we use measured amplitudes as an input?

- several measurements with individual fans / propellers will be combined to form the distributed propulsion system

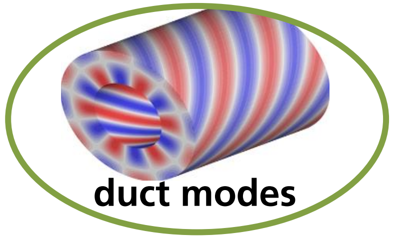
Measurement-informed auralization

analytical input

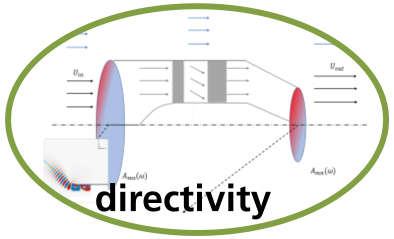
RANS-informed noise prediction

PropNoise

measured input



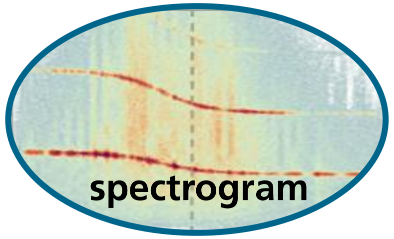
Propagation into the far field



auralization framework

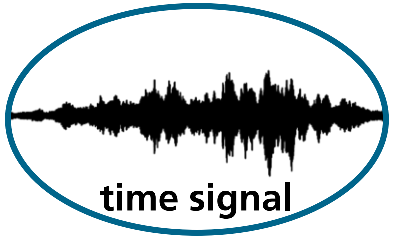
virtual flyover simulation

VIOLIN

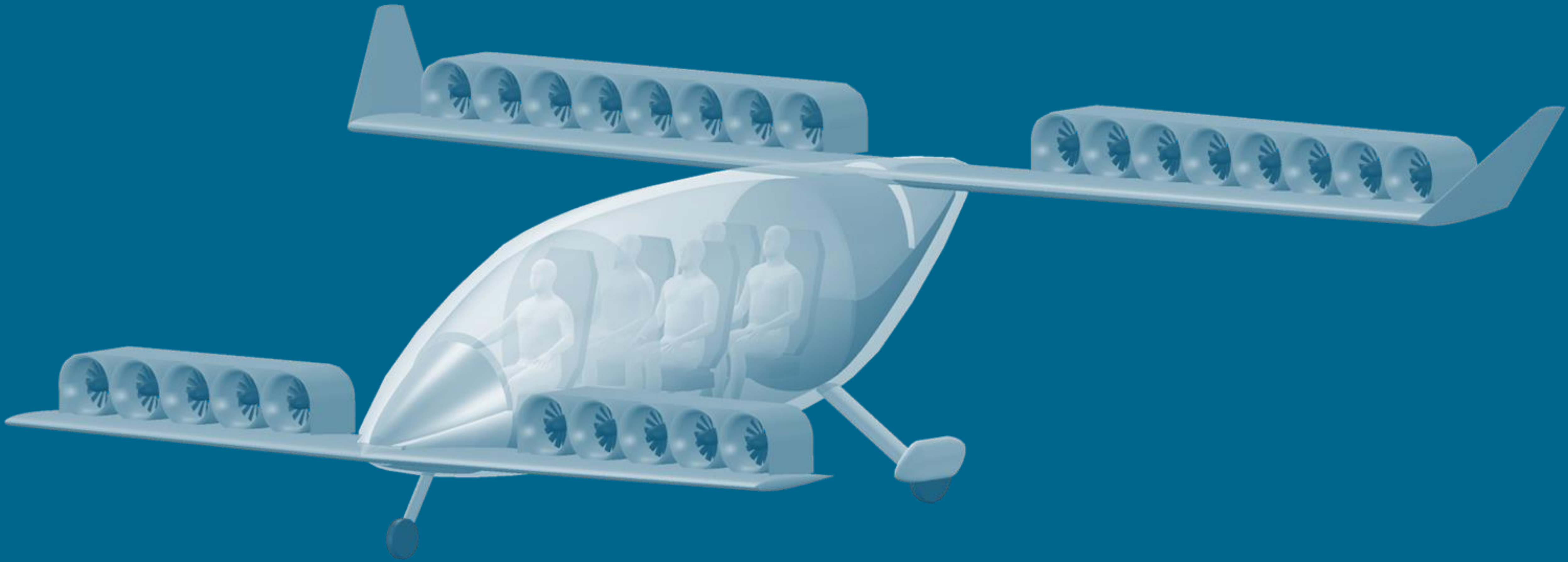


binaural noise synthesis

CORAL



Distributed ducted fans



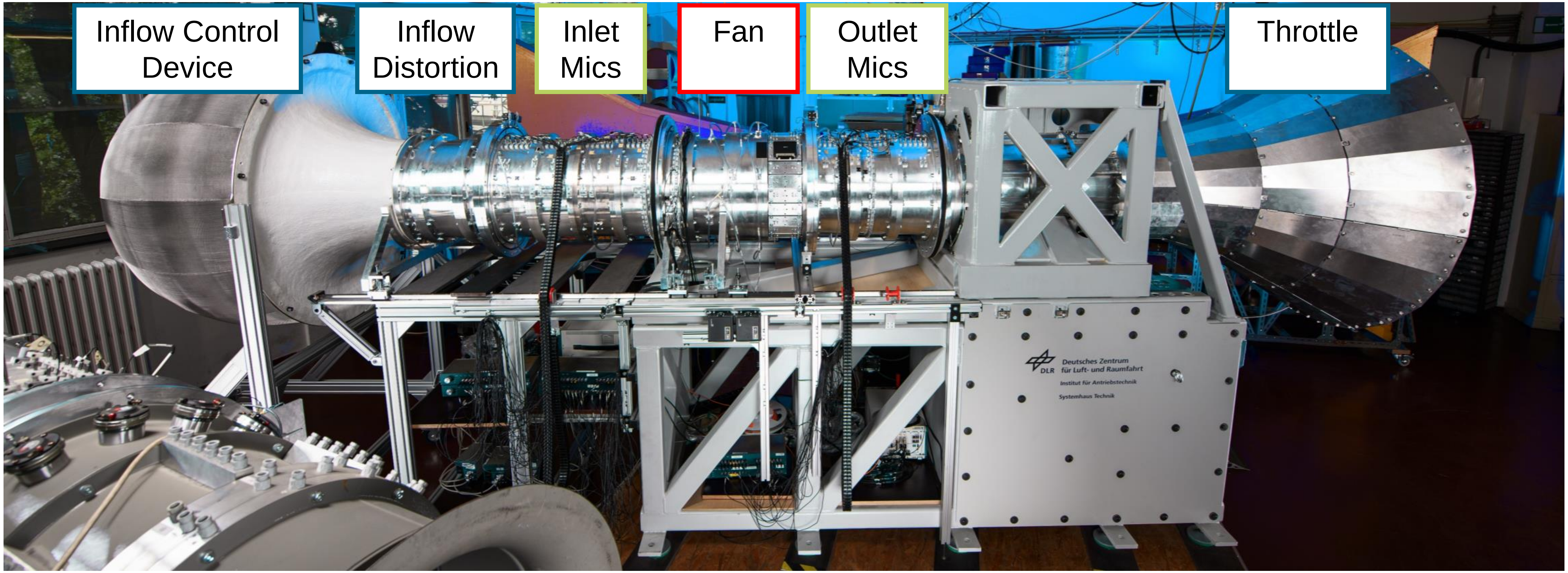
Fan in-duct measurements: setup

$D = 453.6\ \mathrm{mm}$ $n = 4500\ \mathrm{rpm}$ $\dot{m} = 6.9\ kg/s$

$M_{\mathrm{tip}} = 0.3$ $Re = 500\ 000$

at design conditions

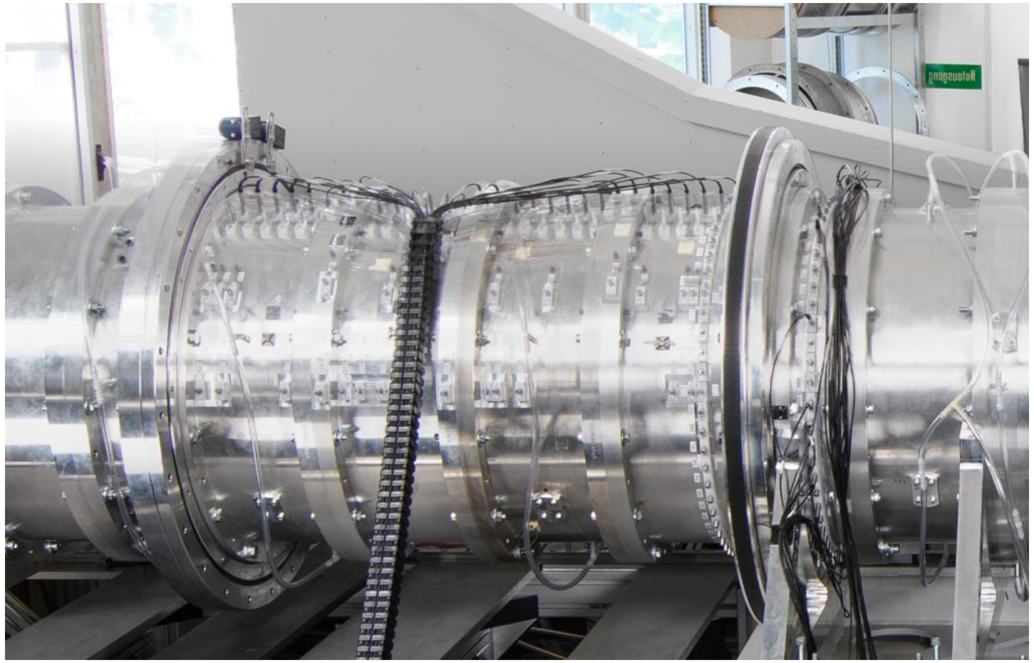
Tapken et al.
AIAA 2021-2314



degrees of freedom: fan design, rotor-stator distance, BLI, rotational speed

Fan in-duct measurements: mode analysis

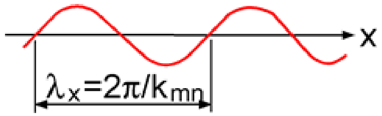
Microphones mounted wall-flushed in rotating duct



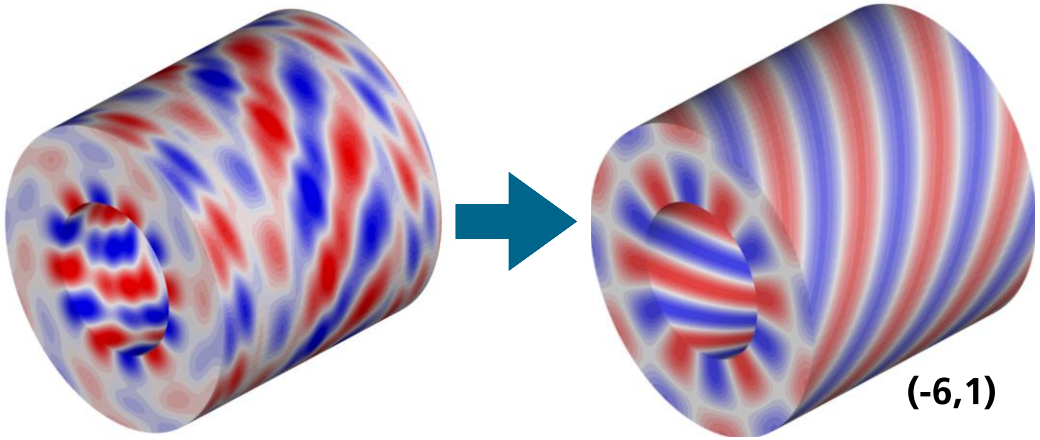
Tapken et al.
AIAA 2014-3318

Radial Mode Analysis

$$p(x,r,\theta) = \sum_{m=-\infty}^{\infty}\sum_{n=0}^{\infty} A^{\pm}_{mn}\, e^{i(k^{\pm}_{mn}x+m\theta)}\, f_{mn}(r)$$



2 different Methods for tonal and broadband noise are used

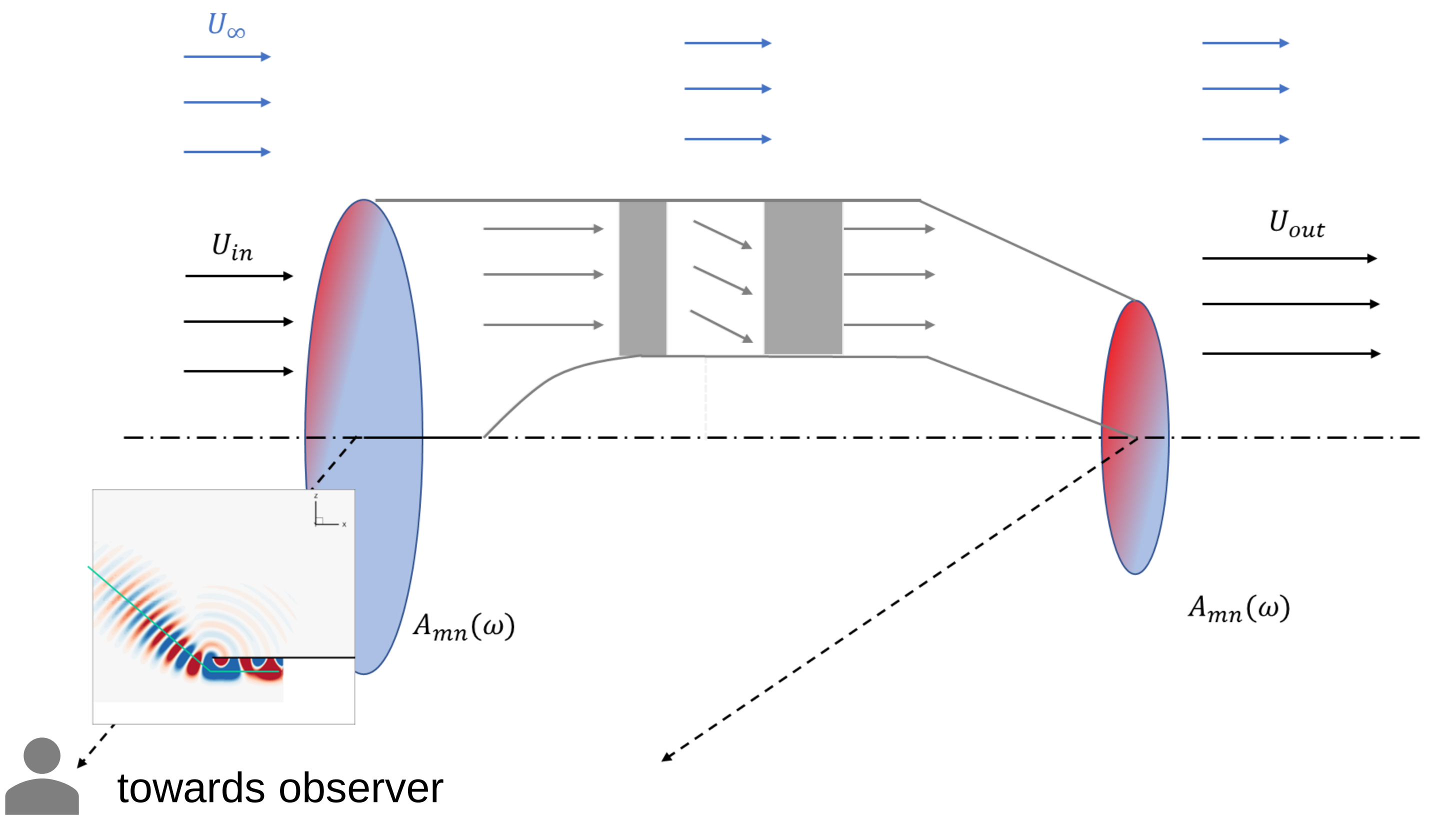


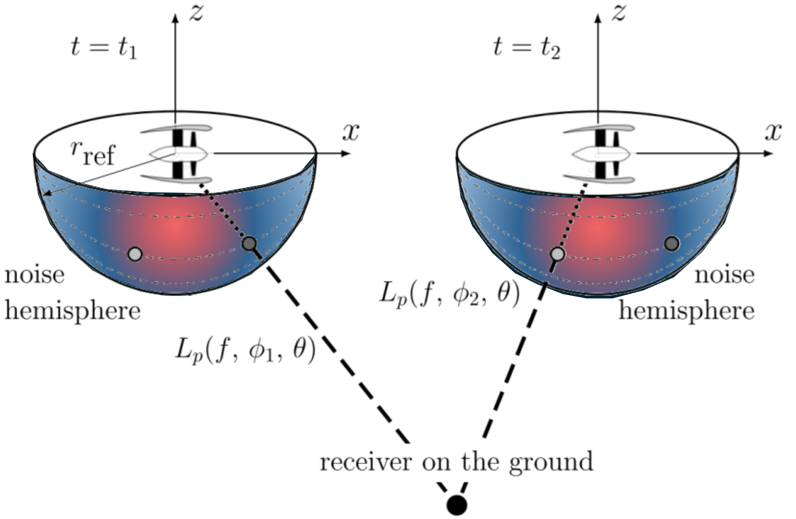
Extrapolation of CRAFT in-duct measurements to far field

input: induct mode amplitudes A_mn from CRAFT experimental results

→ extrapolation to calculate a far-field directivity p_mn

Guérin
AIAA 2017-4037

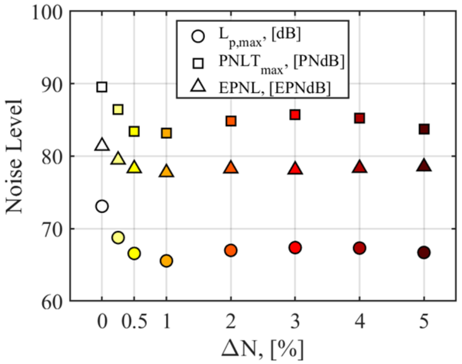


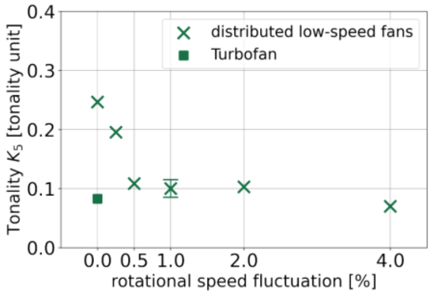


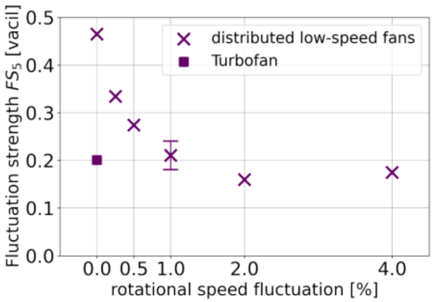
Static rotational speed distribution

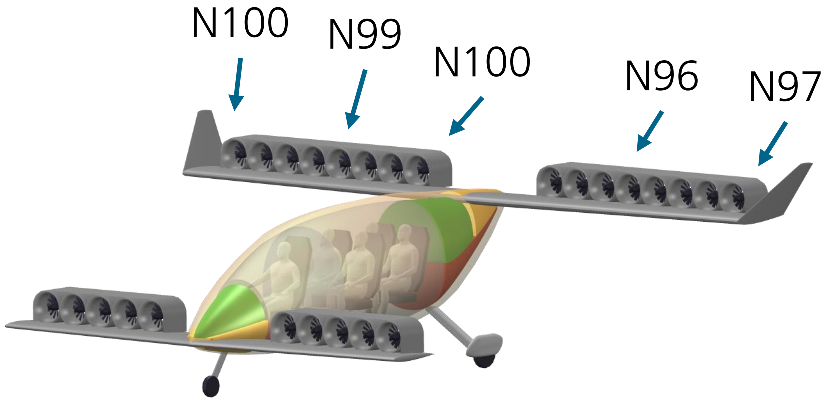
rotational speed variation: measurements performed at 100%, 99%, 98%, 97% and 96% rpm

rotational speed variations seem to considerably affect the **emitted sound levels** and **sound quality**.



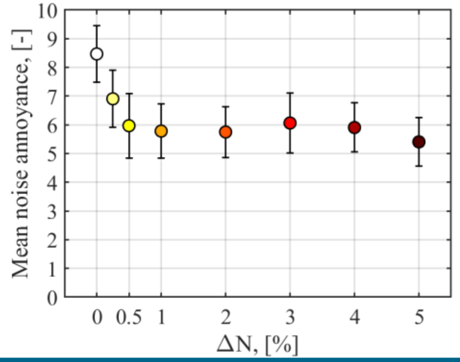






static, **random** (Gauß) **rotational speed variation** applied to the fan stages before flyover

Listening tests: To some extent, **increasing $\Delta N\%$ seems beneficial for sound perception.**



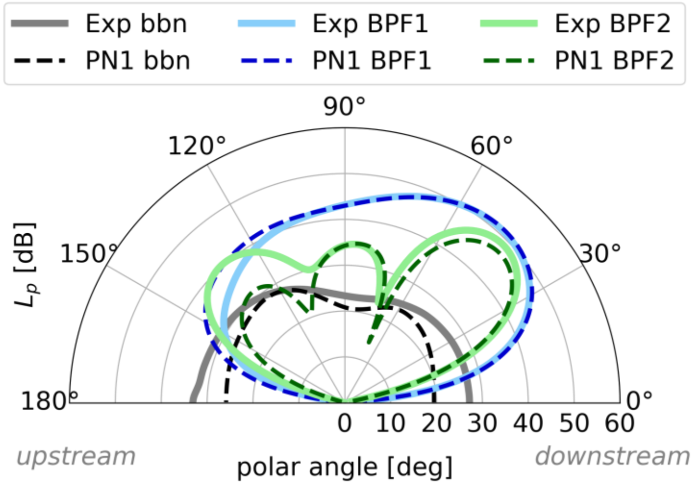
Schade et al., AIAA 2024-3273

Merino Martinez and Schade, InterNoise 2025

Tilt-duct results and comparison with PN

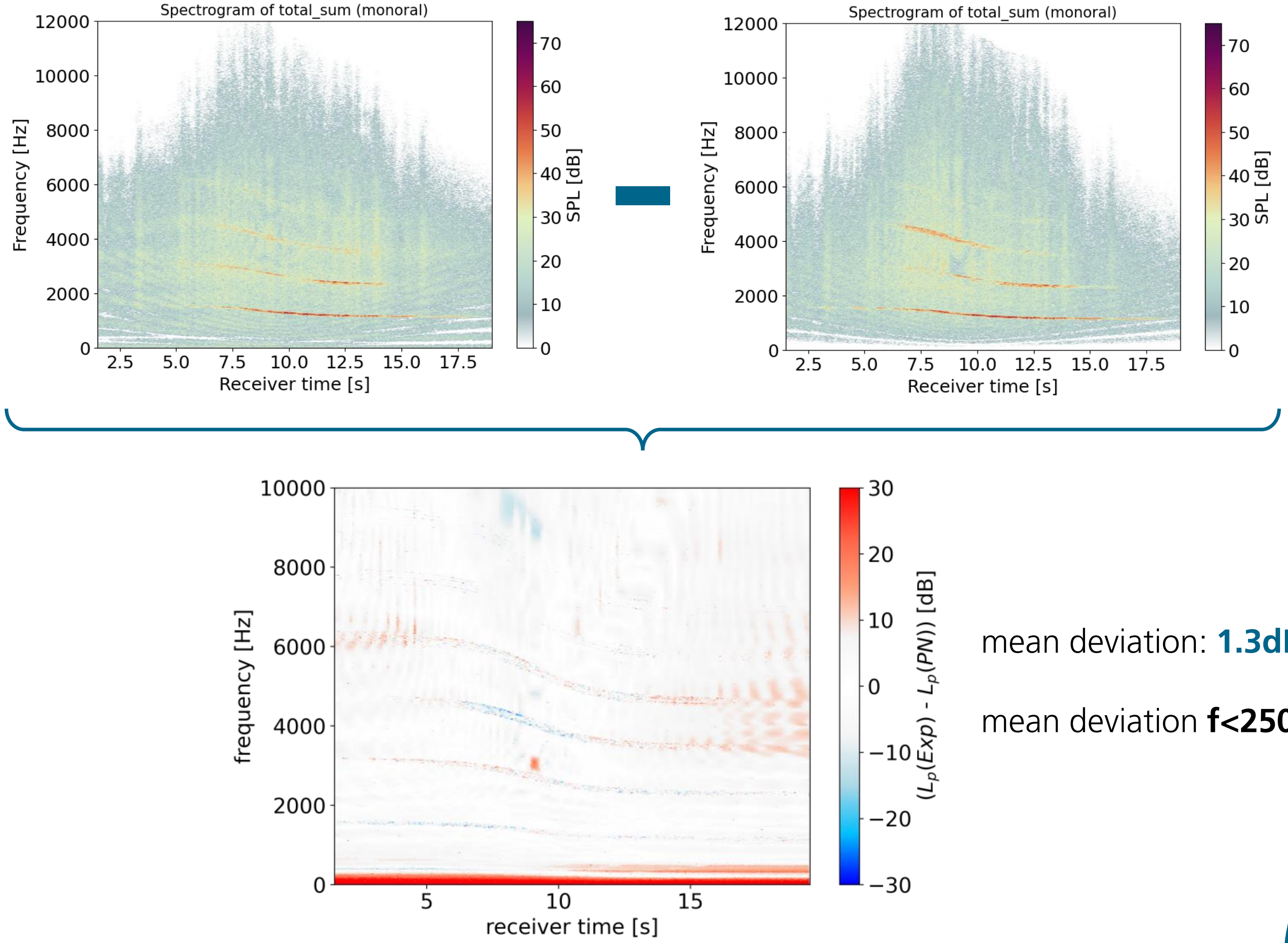
Baseline fan stage

directivities



measured input

analytical input



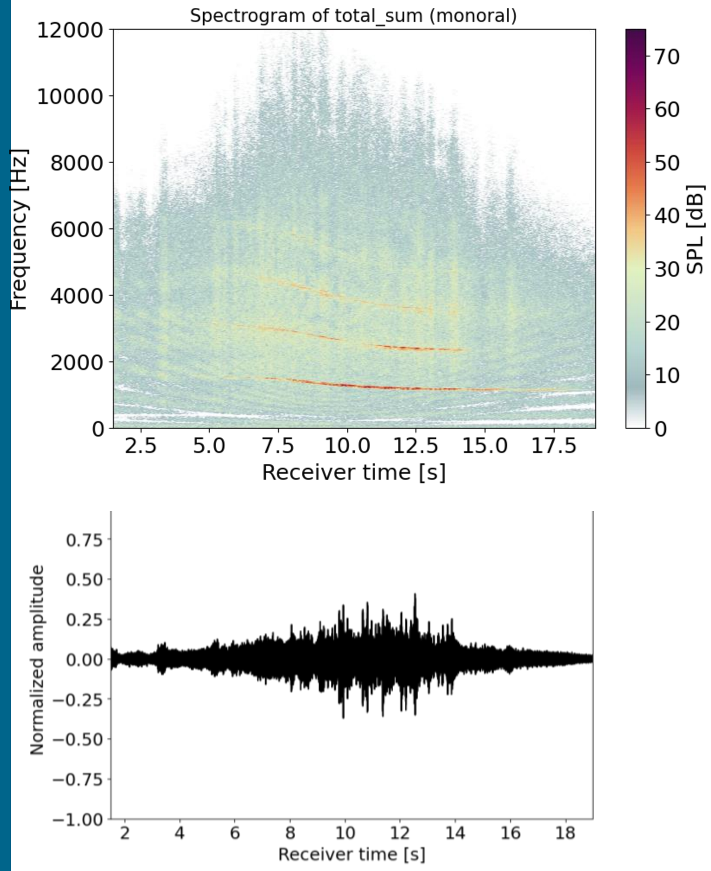
mean deviation: **1.3dB**

mean deviation **f<250Hz**: **28dB**

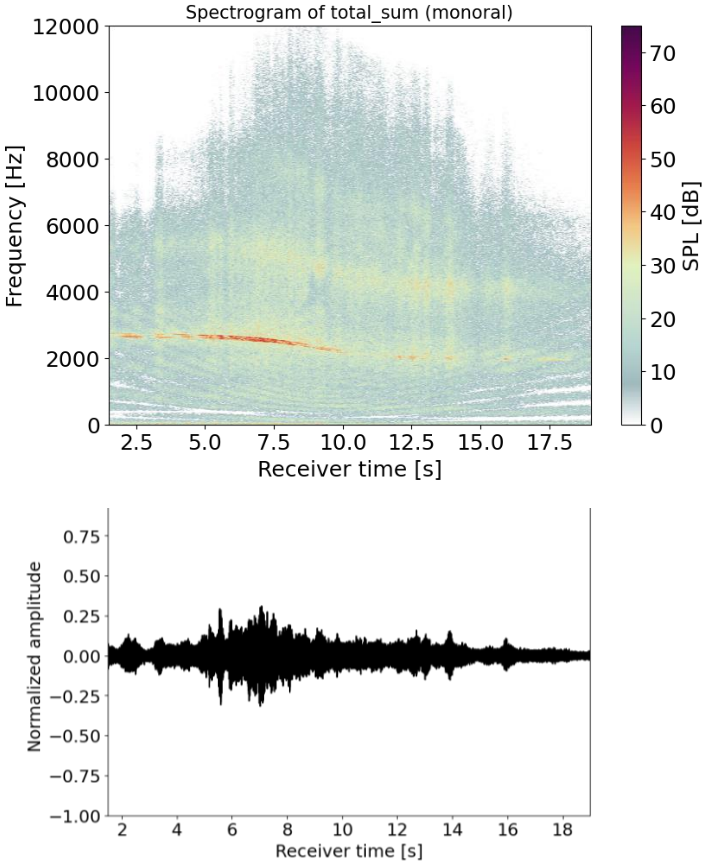
Tilt-duct results and comparison with PN

measured input

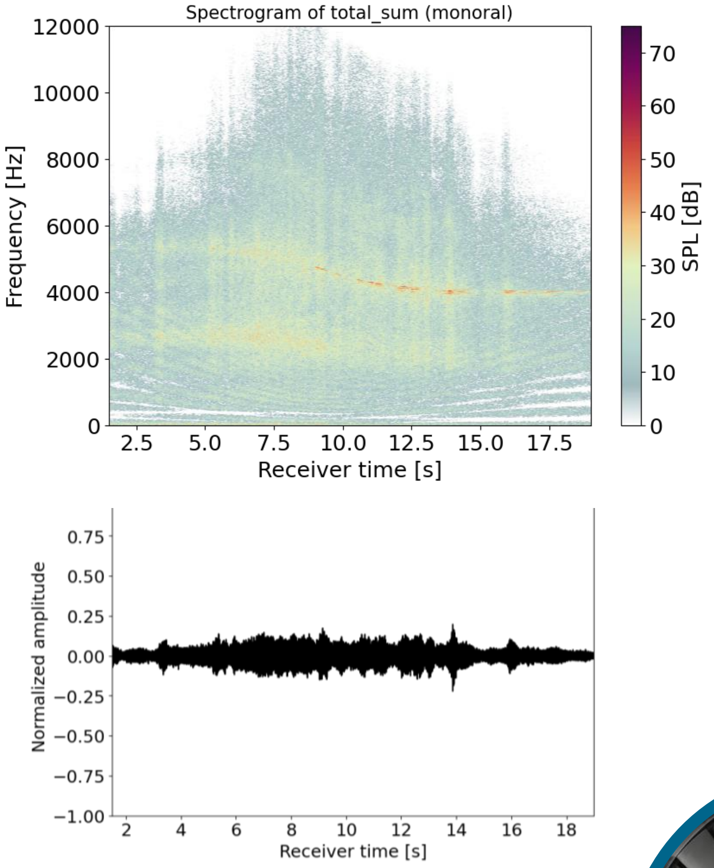
Baseline fan stage



Low-broadband

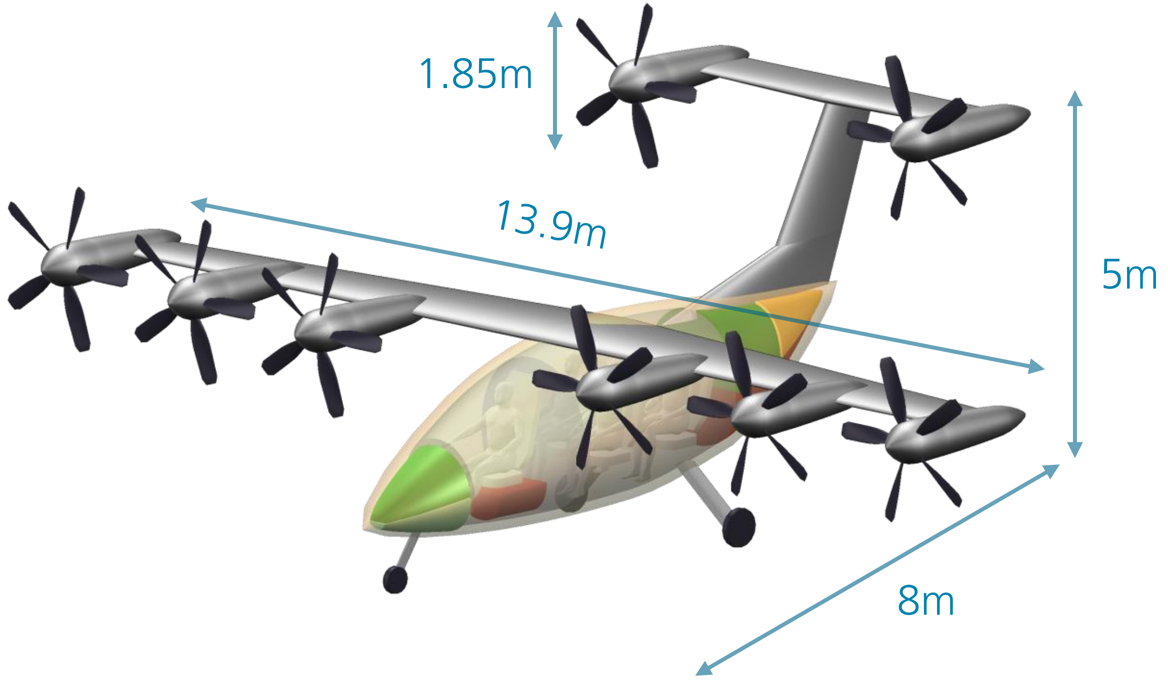


Low-tone



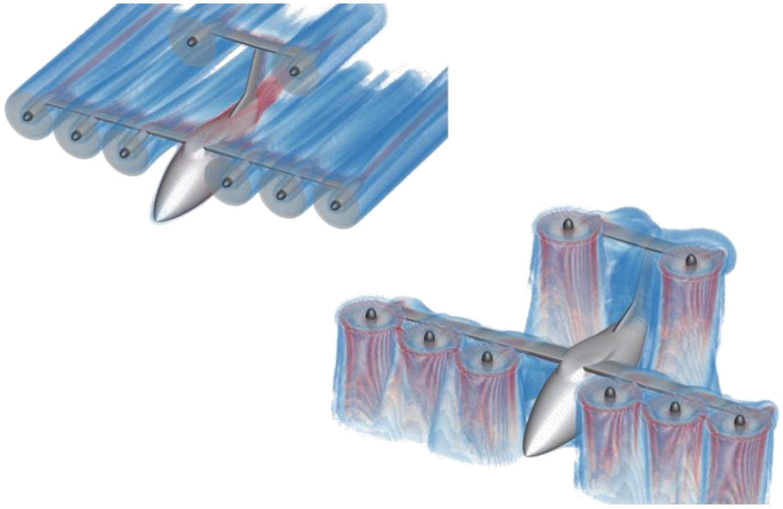
Distributed propeller

Tilt-prop vehicle and fan design *(project VIRLWINT)*



- Payload of **500 kg**
- Mission length of **150 km**
- Cruise speed of **200 km/h**
- Number of propeller **8**

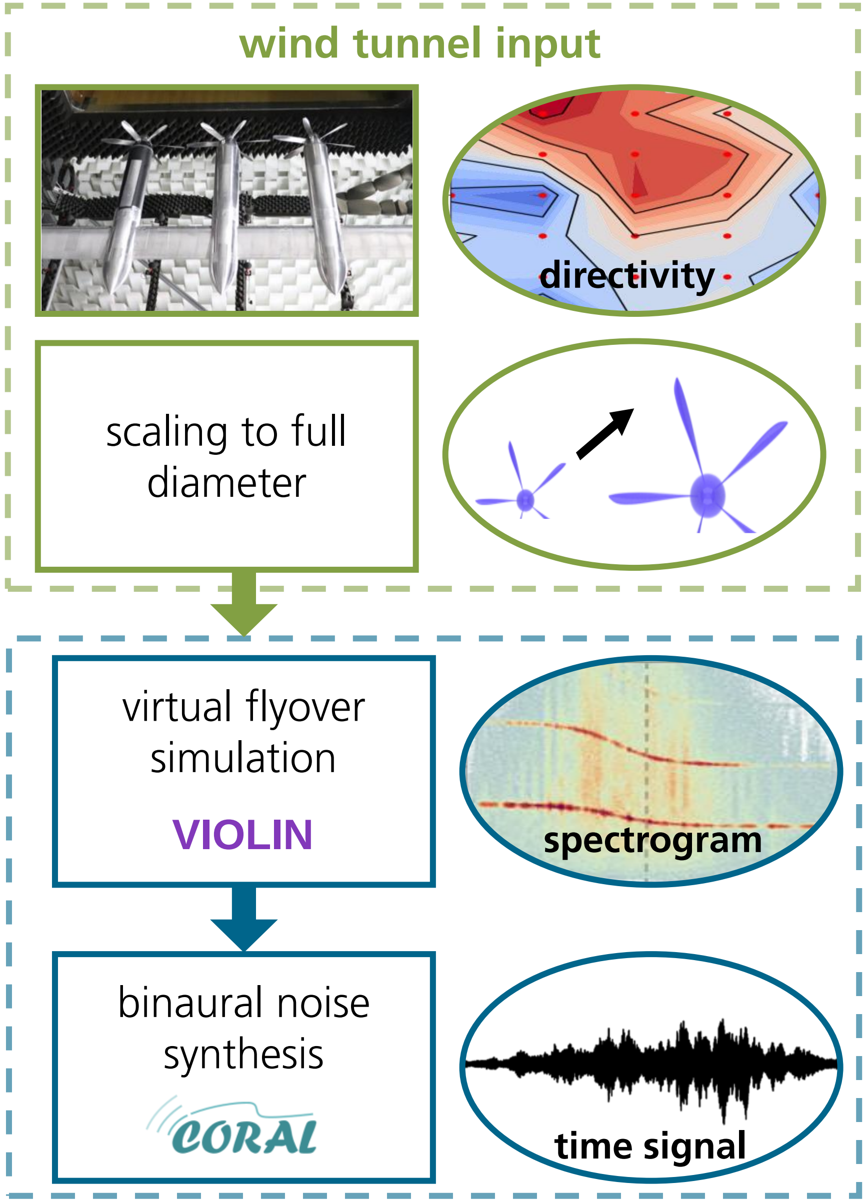
RANS-based aerodynamic design

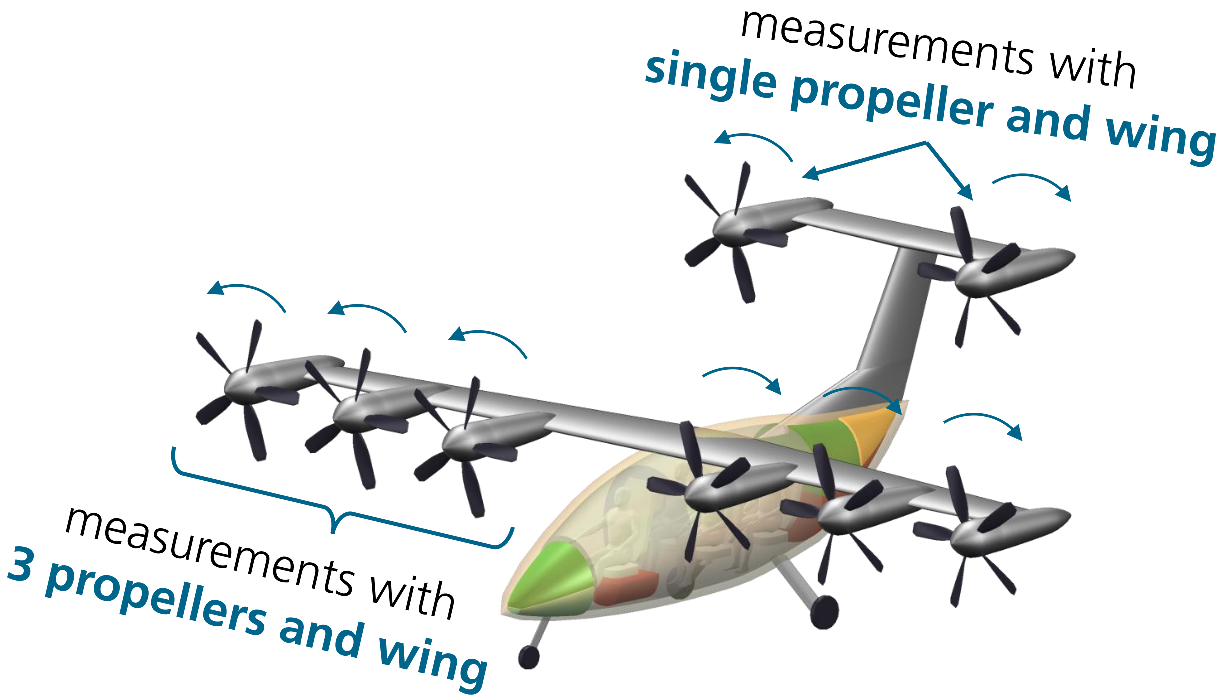


tiltable, variable pitch propeller

	Cruise	Hover
pitch angle [deg]	43	25
Thrust [N]	260	2800
Mtip	0.3	0.5

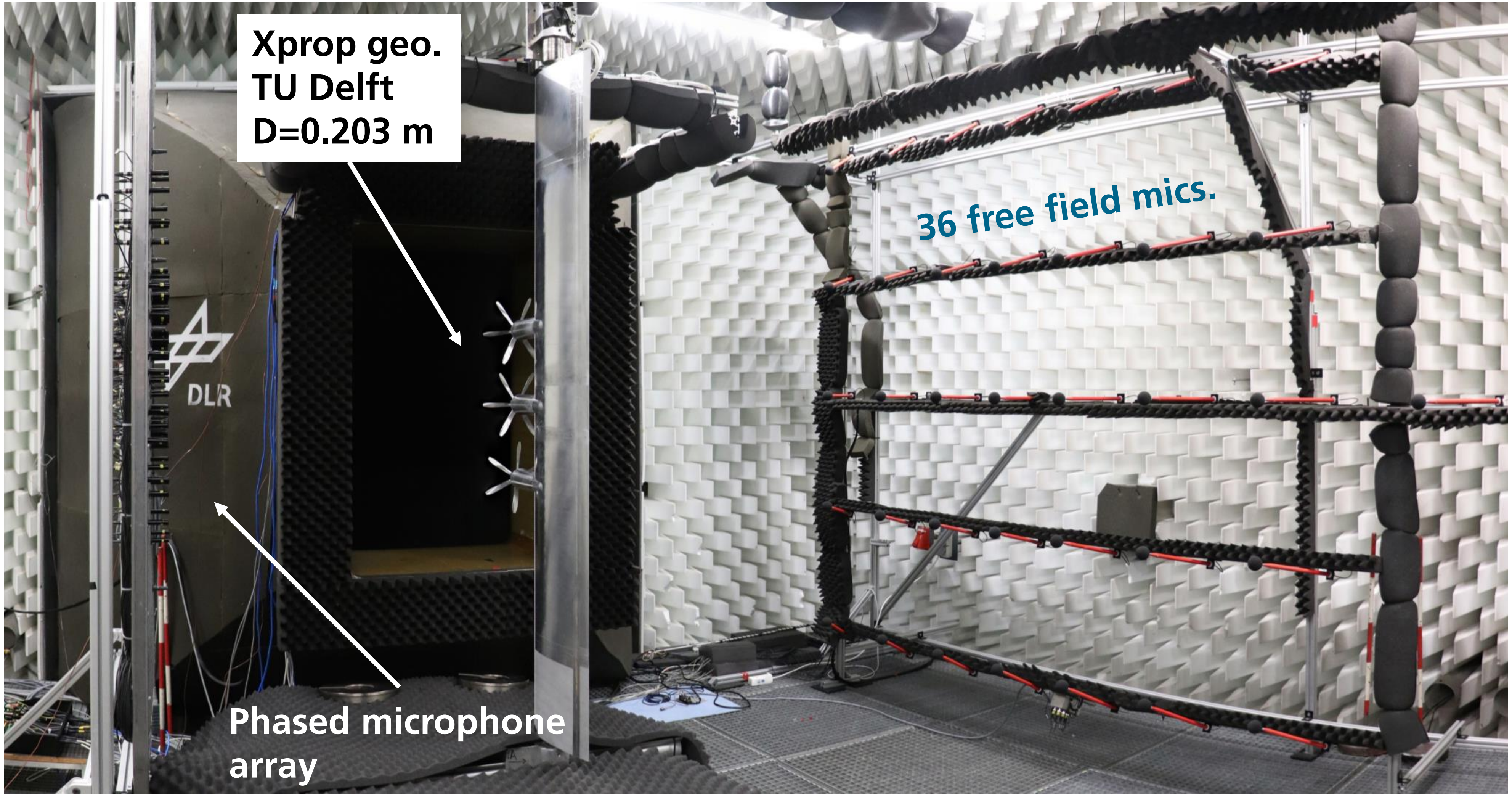
Measurement-informed auralization





Aerodynamic interaction between propellers as well as between propeller and wing included

Propeller: measurement setup (AWB)



degrees of freedom: stagger, rotation direction, phase, AOA, prop spacing, advance ratio, wing flap angle

Propeller: Data preparation

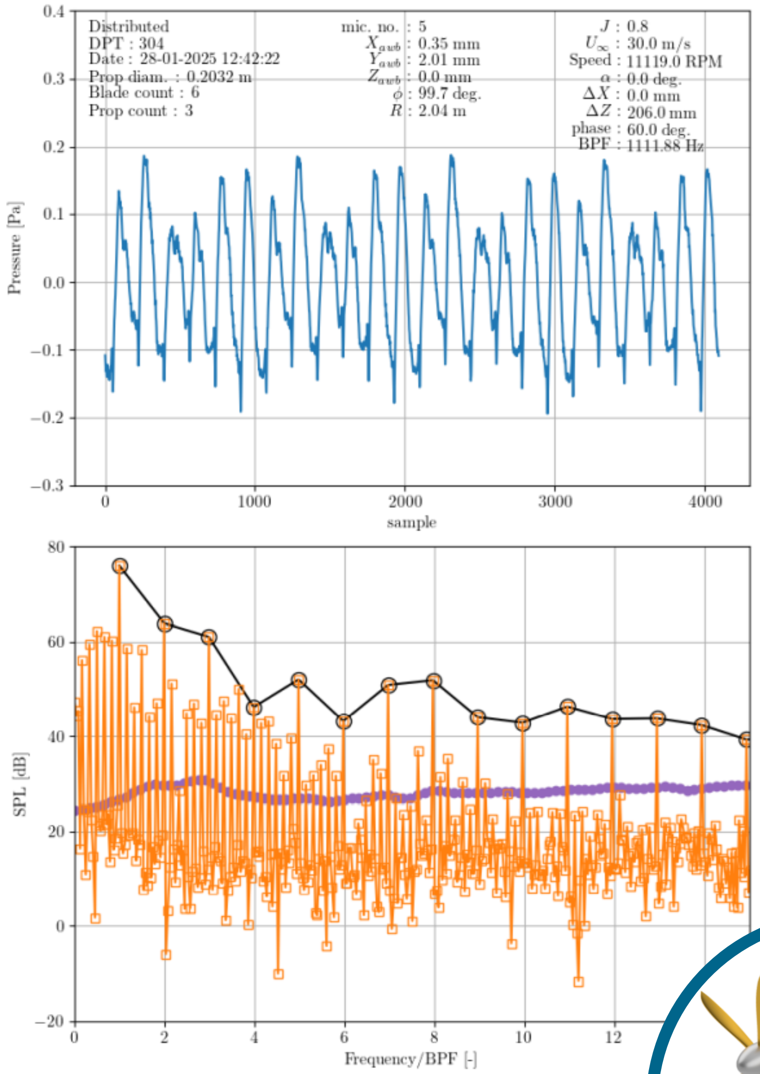
DLR

Wind tunnel corrections

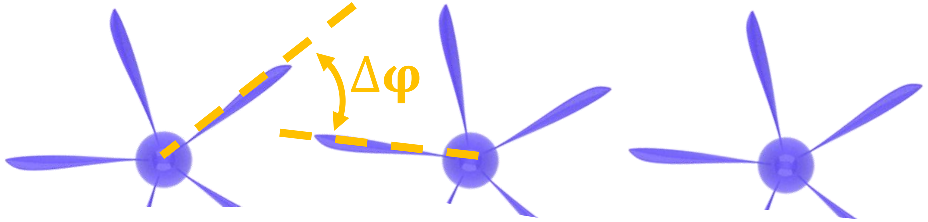
- Shear-layer refraction and convective amplification:
  - use Amiet‘s standard correction
  - Amplitude correction for range 68°< theta < 133° within 1 dB!! **also for curved shear-layers! (Jiao 2017)**
  - Robust propagation path change compensation **also for curved shear-layers! (Jiao 2017)**
- Haystacking:
  - Use beta2 model (P. Sijstma, 2014) for AWB conditions to layout microphone positions
  - Validated using dedicated flow and acoustic measurements in AWB

Data acquisition and processing

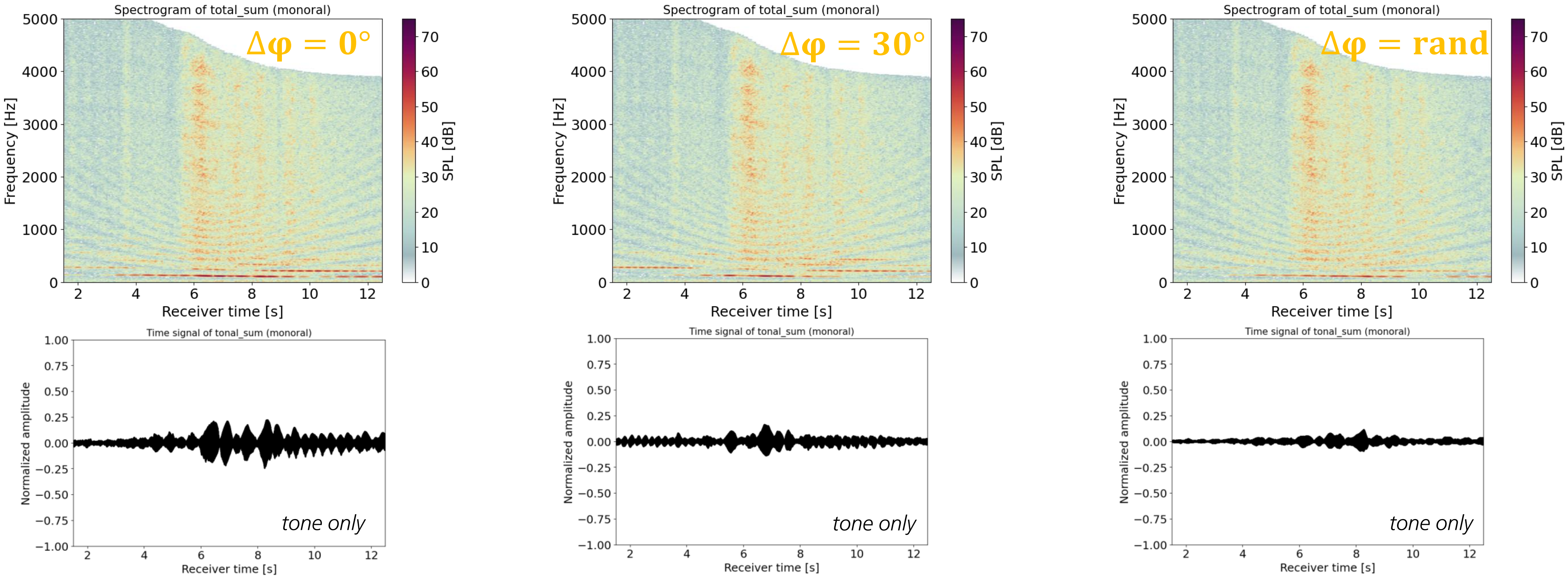
- Sampling rate : 81 kHz
- Acquisition duration : 60 s
- ~2700 fft averages
- Cyclo-stationary data analysis on a 4-rotation basis
- Computation of spectral and cyclo-stationary averages
- Empirical mode decomposition used to filter cyclic components from broadband sound



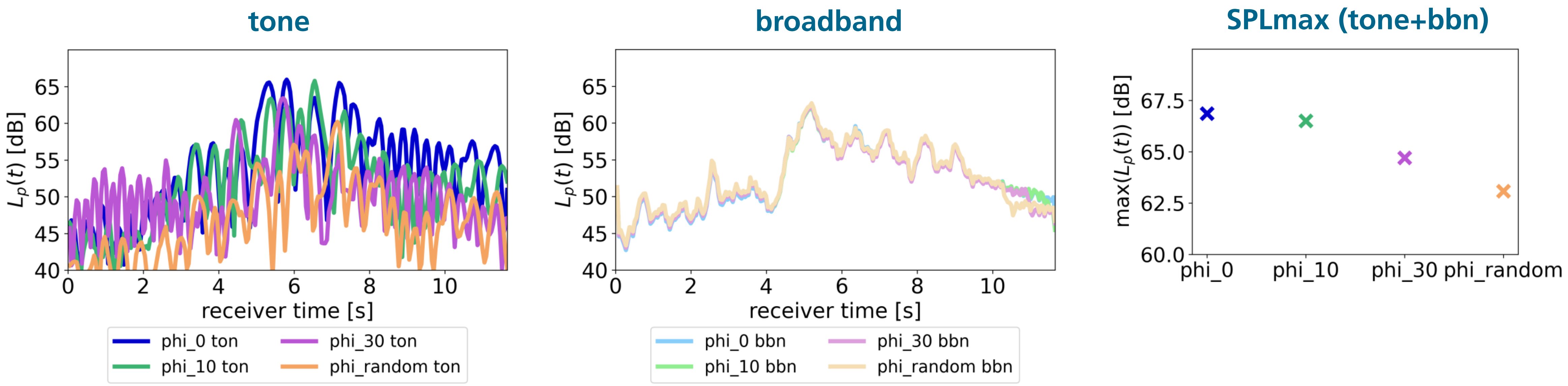
Tilt-prop results: Impact of propeller clocking



$\Delta\varphi = 0°, 30°$ **and random**



Tilt-prop results: Impact of propeller clocking

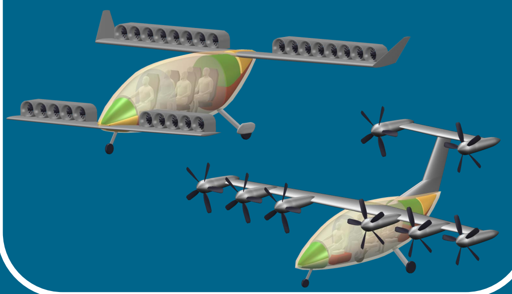


- the relative **blade-to-blade angle** noticeably **impacts tonal noise immission**
- **lowest noise levels** for $\Delta\varphi = 30°$ (half propeller spacing) and **random**

✈ *similar trends observed in Monteiro et al. (AIAA 2024-3321)*

Summary

propulsion system



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acoustic measurements

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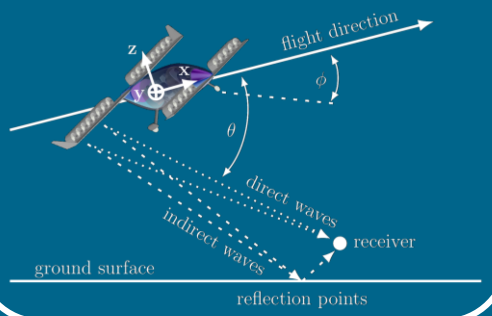
auralization



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sound perception

- **measurement-informed auralization framework** to obtain UAM flyover sounds for psychoacoustic studies
- extensive fan and propeller **measurement campaigns** (parameter variations)

What's next?

- **auralization studies** to acoustically and psychoacoustically **investigate the degrees of freedom**, such as clocking positions, prop and rotor-stator distances, rotation directions…
- **listening test**
- **sound quality** analysis

Acoustics of Drones and
Urban Air Mobility Vehicles

Thank you for your attention!

German Aerospace Center (DLR)

Department of Engine Acoustics

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