

Measurement-Based UAV Noise Modeling, Auralization and Perceptual Evaluation

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The rapid growth of unmanned aerial vehicle (UAV) operations in applications such as logistics, search and rescue, recreational aviation, and urban air mobility (UAM) has increased the importance of accurately assessing their environmental impact, particularly regarding community noise and public acceptance. Acoustic emissions are among the primary factors influencing societal acceptance of UAV and UAM operations, making measurement, realistic prediction, assessment, and reproduction of drone noise essential for both technical development and regulatory processes. This study presents a comprehensive workflow that combines detailed acoustic measurements, immersive auralization and advanced noise prediction, to enable realistic evaluation of UAV sounds in virtual and operational environments.

The methodology is based on extensive UAV noise measurements conducted within the German Aerospace Center (DLR) projects AREA U-Space and IAM-OSA. These measurements capture the acoustic signature of different UAV platforms and flight manoeuvres. The recorded data are analysed and post-processed into acoustic spheres representing the frequency-dependent sound directivity of the vehicles. This is done by utilizing a specialized MEMS microphone array. The acoustic signal is also recorded with on-board microphones, yielding the self-noise of the UAV through post-processing. Furthermore, recordings with a single microphone are performed for different flyover paths in both urban and rural environments with stationary receiver positions. Complementary auralization approaches are investigated for each of these datasets. They reach from generating artificial sound signals based on the measured acoustic directivities using DLR's standard aircraft noise prediction tool PANAM to using the raw single microphone data. PANAM enables the calculation of conventional noise metrics, including A-weighted sound pressure levels and contour areas, as well as advanced psychoacoustic descriptors. Furthermore, the processed signals provide the foundation for high-fidelity auralization of UAV flyovers and other operational scenarios.

All approaches incorporate physically relevant propagation effects, including Doppler shift and ground reflections, resulting in realistic and repeatable acoustic renderings. The generated sound scenes are validated by comparison with real fly-by recordings using psychoacoustic metrics, demonstrating their capability to reproduce characteristic UAV noise under different operating conditions.

To facilitate perceptual acceptance studies, the developed auralization pipeline is integrated into the Unreal Engine, enabling interactive virtual environments in which

UAV sound is accurately rendered. This immersive framework allows realistic simulation of individual flights as well as future integration into larger U-Space scenarios involving multiple vehicles, routing concepts, and community exposure assessments. Such virtual environments provide a controlled and repeatable platform for investigating human perception, annoyance, acceptance, and interaction with UAV traffic under varying operational and environmental conditions.

Beyond research applications, the presented workflow establishes a foundation for comprehensive acoustic assessment throughout the UAV development process. By linking detailed measurements, standardized noise prediction with PANAM, advanced psychoacoustic analysis, and immersive auralization, the framework enables consistent evaluation of UAV noise from single-event recordings to complex operational scenarios. It also offers promising opportunities for supporting certification processes and regulatory assessments that will become increasingly important as unmanned aerial mobility expands. The current study summarizes the state of this integrated assessment process, discusses its present capabilities, and identifies future developments required to support large-scale implementation of UAV operations while addressing community noise and societal acceptance.

Biography

Leon Steinhoff



Leon Steinhoff is a doctoral researcher at the German Aerospace Center (DLR) for the Institute of Aerodynamics and Flow Technology in Göttingen. He holds bachelor's and master's degrees in Aerospace Engineering. His current research focuses on UAV acoustics, noise assessment, and auralization.