Transportation Research Part D 99 (2021) 103020

Contents lists available at ScienceDirect

Transportation Research Part D

journal homepage: www.elsevier.com/locate/trd

Validation of an airline pilot assistant system for low-noise approach procedures

David Jäger [a], Christoph Zellmann [a,1], Jean Marc Wunderli [a,*], Marco Scholz [b,2], Fethi Abdelmoula [b], Martin Gerber [c]

[a] Empa Laboratory for Acoustics/Noise Control, Überlandstrasse 129, 8600 Dübendorf, Switzerland
[b] German Aerospace Center DLR, Lilienthalplatz 7, 38108 Braunschweig, Germany
[c] Swiss Skylab Foundation, c/o Air Force Center, Überlandstrase 271, 8600 Dübendorf, Switzerland

ARTICLE INFO

Keywords:
Aircraft noise
Noise abatement operational procedures
Pilot assistance system
Continuous descent approach
LNAS
sonAIR

ABSTRACT

The recently developed airline pilot assistance system LNAS (Low Noise Augmentation System) supports pilots in optimizing approaches in terms of fuel consumption and noise emission by predicting the optimal vertical trajectory and best speed, configuration, and landing gear setting. The system continuously updates recommendations to provide the energy-optimal profile at any time. The noise reduction potential of the latest LNAS version was tested during a flight campaign in 2019 at Zurich Airport, Switzerland, using a dedicated Airbus A320 research aircraft. 43 LNAS-assisted and 21 conventional approaches were analyzed. Acoustic measurements taken at six microphone positions along the glide path revealed reductions in average sound exposure levels of up to 1.8 dBA when LNAS was used. Complementing detailed single-flight simulations using the aircraft noise program sonAIR confirmed the large noise reduction potential of LNAS, which may help reducing sound exposure in certain areas by up to 2.5 dBA.

1. Introduction

The European Aviation Environmental Report for 2019 predicts an increase of the number of flights in Europe until 2040 of 42% under the base traffic forecast (EASA, 2019). While the COVID-19 pandemic strongly impacted and continues to impact air traffic, it is likely that the general growth trend will resume in the next years. Thus, the number of people affected by aircraft noise will also increase again. The challenge therefore is to decrease overall aircraft noise despite an increasing number of flights.

The most effective way to reduce aircraft noise is the acoustic improvement of the aircraft fleet. This process has been ongoing over the last decades (NASA, 2020) and is likely to partially compensate the noise increase caused by the traffic growth. However, the service life of current aircraft types and the development cycles of new aircraft is long, therefore additional measures need to be considered in order to accelerate aircraft noise mitigation, as proposed in ICAOs Balanced Approach (ICAO, 2008).

Noise reduction can be achieved in a shorter timeframe by optimizing departure and approach procedures. The approach in particular is a work-intense flight phase for pilots, as they have to manage speed, altitude and aircraft configuration while reacting to changing winds, traffic and instructions from air traffic control (ATC). This intense workload makes it challenging to perform an

* Corresponding author.
E-mail address: jean-marc.wunderli@empa.ch (J.M. Wunderli).
[1] Present address: n-Sphere AG, Räffelstrasse 29, 8045 Zürich, Switzerland.
[2] Present address: Volkswagen AG, Berliner Ring 2, 38440 Wolfsburg, Germany.

https://doi.org/10.1016/j.trd.2021.103020

energy-optimal approach. As a consequence, approaches are often flown either faster or slower than optimal. Fast approaches need to be slowed down by using speedbrakes and/or extending the landing gears early, causing additional aerodynamic noise. An investigation of several thousand approaches on Frankfurt Airport, Germany, revealed that 20% of approaches had already extended the landing gear at roughly seven nautical miles or further from the runway threshold, which is well beyond the required stabilization distance of four nautical miles (Abdelmoula and Scholz, 2018). Slow approaches, on the other hand, need additional engine thrust to compensate the drag of the high-lift system, which can increase noise emission by several dBA (Snellen et al., 2017). Both cases therefore lead to avoidable noise along the approach trajectory.

To help avoid such unnecessarily loud approaches, an airline pilot assistance system, named Low Noise Augmentation System (LNAS), was recently developed by the German Aerospace Center (DLR) (Kühne et al., 2018). It is an onboard assistance system that helps pilots manage the energy budget during approach from cruising altitude down to stabilization height (1000 feet above runway level). By helping the pilot perform an energy-optimized approach, LNAS not only aims at reducing noise but also to save fuel. The system features three main elements: pre-planning, continuous correction and an energy-based display. Pre-planning involves a simplified simulation of an ideal vertical approach trajectory including aircraft configuration based on pre-set glide angle, current position, speed, weight and wind speed at current altitude as well as on the ground. The predicted trajectory aims at reaching stabilization conditions with minimal engine thrust and without the use of speedbrakes. During approach, a continuous real-time correction is performed to account for changing wind conditions and commands from ATC, thereby providing the energy-optimal profile at any time. The relevant and continuously updated information is displayed to the pilot on a screen in the cockpit.

A first version of LNAS was designed to optimize the Low Drag Low Power (LDLP) approach procedure. It was tested in 2016 by carrying out a number of test flights with DLRs Airbus A320 Advanced Technology Research Aircraft (ATRA) at Frankfurt Airport, Germany. Measurements of those flights demonstrated the capability of LNAS to save fuel and reduce sound exposure levels by up to two decibels compared to regular airline approaches (Abdelmoula and Scholz, 2018; Scholz and Abdelmoula, 2017).

In recent years, many airports, such as Zurich Airport in Switzerland, started to recommend the Continuous Descend Approach (CDA) whenever traffic density and weather conditions allow it. This approach procedure aims at avoiding horizontal flight segments, thereby keeping the aircraft at higher altitudes for longer and reducing phases of increased engine thrust. It is capable of reducing the noise impact both in terms of sound pressure metrics as well as sound quality metrics when compared to traditional approach procedures (Pereda Albarrán et al., 2017).

To further optimize CDAs, LNAS was extended to be able to calculate CDA trajectories. This new LNAS version was tested during a one-week flight campaign in September 2019 at Zurich Airport, Switzerland. This paper focusses on the acoustical evaluation of these test flights using noise measurements and simulations. The main goal was to localize areas where LNAS achieved a beneficial effect and to quantify those noise reductions.

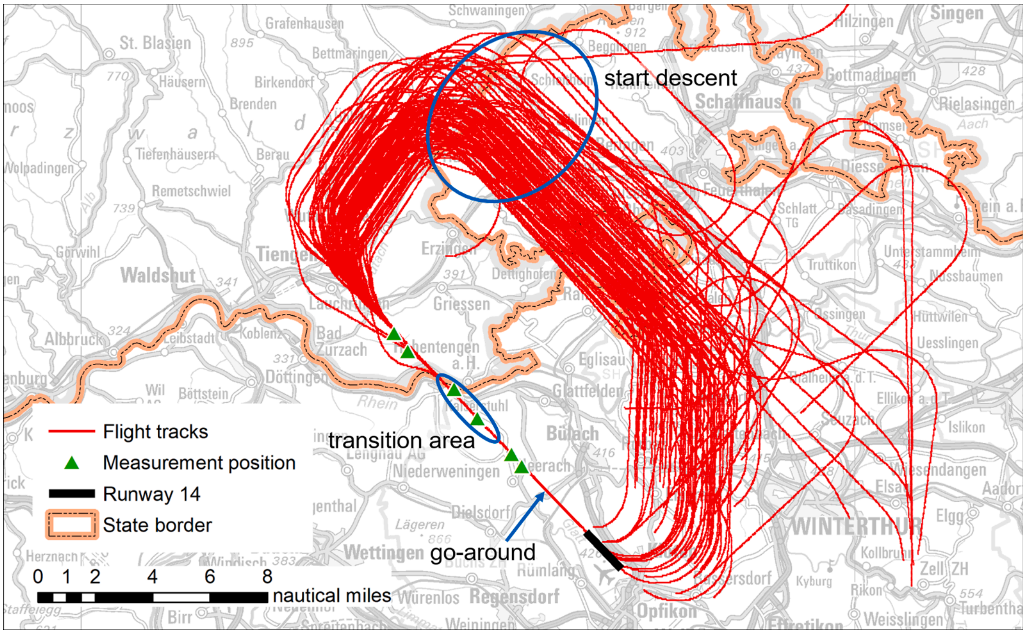

Fig. 1. Flight tracks of all ATRA flights during the test campaign at Zurich airport. Map source: Federal Office of Topography.

2. Methods and data

2.1. Flight test

The flight test campaign took place from September 9th to 13th, 2019, at Zurich Airport. Flights were performed with DLRs research aircraft Airbus A320 ATRA. The A320 represents the most widely used aircraft type for short- and medium-distance flights, making it the ideal test platform. The ATRA was loaded with additional ballast to achieve a typical take-off weight of 65.5 t during the test campaign. Furthermore, it was retrofitted with vortex generators to suppress a dominant tone generated at the fuel overpressure protector cavities (Zellmann et al., 2018). Such vortex generators are installed on the A320 aircraft family of most large airlines today, including the regular airline measured in this study (see below). Note that another tonal component generated at the nose landing gear of the A320 aircraft family (Merino-Martinez et al., 2016; Merino-Martinez and Snellen, 2020) was still present in the recordings, but did not skew the measurement results as it influenced the noise signature of the ATRA and the regular airline A320 fleet equally.

Test flights took place daily from 8:15–10:30 AM and 1:15–4:00 PM. Approaches were flown from 7000 feet above mean sea level toward runway 14, ending with a go-around at 800 feet above ground and climbing back to the initial altitude to start the next approach (see Fig. 1). In addition to the DLR flight crew, 23 regular airline pilots took part in the test. After each approach, the pilot flying was switched, thereby reducing short-term learning effects and obtaining maximum variability of conditions for each pilot. All test flights took place within normal operation conditions of the airport without special treatment by ATC.

A total of 91 approaches were flown, 57 with the help of LNAS and 34 without. Pilots flying with LNAS were trained in the usage of LNAS in the simulator before the flight tests. Pilots flying without LNAS were unfamiliar with the system, but used to the aircraft type, airport and approach procedure. They were instructed shortly before the flight to carry out a CDA.

To ensure comparability between flights with and without LNAS, the flight data recordings (FDR) of all ATRA flight were analyzed after the test campaign. Flights falling into one of the following categories were excluded from further analysis:

- Engine anti-ice system was turned on due to total air temperatures below 10 °C. This increased the idle rotational speed of the engines, thereby reducing comparability of idle approaches.
- Approach trajectory contained horizontal flight segments (non-CDA).
- The pilot deviated from the procedural specifications.
- ATC gave speed requirements, overriding the LNAS recommendations.
- Approach situations occurred that were not (yet) implemented in LNAS.
- ATC-given information on the remaining track-miles were entered into LNAS before the aircraft reached its final heading, i.e. while still flying in a curved approach segment, thereby leading to false predictions.

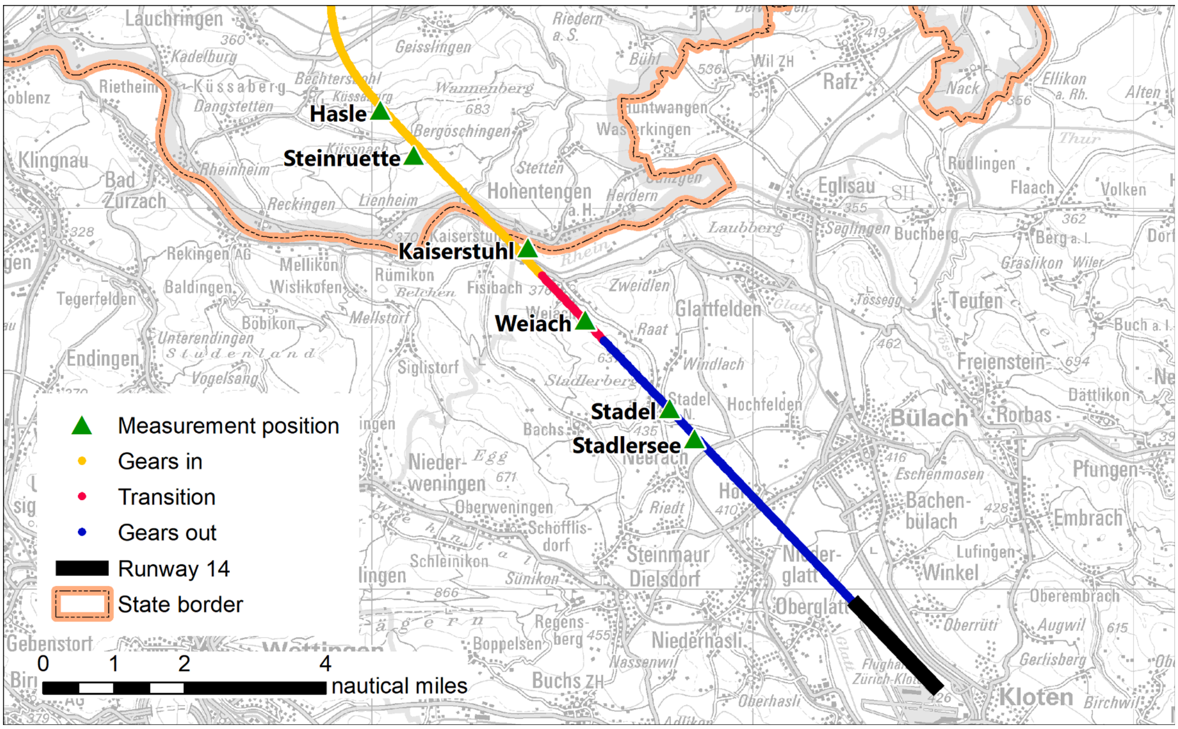

Fig. 2. Measurement positions along approach route toward runway 14 at Zurich Airport. The colors of the approach path display exemplary landing gear positions. Map source: Federal Office of Topography.

This left 64 valid approaches for further investigation. Of those flights, 43 were performed with and 21 without LNAS.

ATRA approaches without LNAS were used as control group to assess the noise reduction potential of LNAS. They were supposed to represent regular approaches. However, even without the assistance of LNAS, pilots were flying in an artificial test environment under close observation by other pilots and a wide range of measurement equipment, which might have affected their performance. To ensure that ATRA flights without LNAS acoustically represented a realistic baseline, regular airline A320 approaches were also measured during the same timeframe and compared to the ATRA flights. No flight track data was available for the regular airline approaches.

2.2. Acoustical measurements

2.2.1. Measurement setup

The noise exposure on the ground was measured acoustically with six mobile measurement stations along the northern approach route S14 of Zurich Airport. The stations were installed directly underneath the glide path in distances between 3.4 and 9.7 nautical miles from the runway threshold. Four stations were located in Switzerland and two in Germany (Fig. 2). Measurement positions in larger distances from the airport were considered but found to be infeasible due to bad signal-to-noise ratio and an increased horizontal spread of flight tracks.

Each measurement station consisted of a ½“ class 1 microphone of type NTi M2230 with WP30 wind screen, installed on a metal pole four meters above ground. The audio signal was recorded as 24-bit MONO signal WAV files in 48 kHz using a sound-level meter of type NTi XL2. A GPS antenna provided a highly accurate time stamp. The stations were equipped with a solar panel for energy self-sufficiency and a mobile phone transmitter for remote control and data transmission.

All measurement stations were calibrated at the beginning of the test week. They were operated daily from 7:45–12:00 AM and 1:00–7:30 PM. During these time windows, all approaches toward runway 14 were recorded, including regular air traffic.

2.2.2. Post-processing

The continuous audio recordings were cut into individual WAV files for each overflight by time correlation with FDR data for the ATRA flights and with daily lists of movements provided by Zurich Airport for all regular approaches. Each clip was then automatically and manually checked for usability by analyzing the spectrogram and, if necessary, listening to the audio recording. In total, 5.8% of all single flight recordings were excluded from further analysis due to background noise contamination.

Acoustic metrics were calculated directly from the calibrated audio recordings. The maximum level $L_{AS,max}$, based on the level-time histories of individual overflights smoothed with a time constant of one second (SLOW), and the sound exposure level L_{AE} over the entire overflight were used in further analysis. Both measures were A-weighted.

2.3. Simulation

Noise measurements only offer point assessments at specific locations of the entire noise footprint. To gain an understanding of the area-wide effect of LNAS on noise impact, each ATRA flight was also acoustically simulated using the aircraft noise simulation model sonAIR (Wunderli et al., 2018). sonAIR was developed specifically to accurately simulate single flights and noise abatement flight procedures. It allows the calculation of sound exposure levels at specific locations on the ground as well as at a receiver grid for the generation of noise maps.

The acoustical emission models feature three-dimensional directivities and are separated into engine and airframe noise (Zellmann et al., 2017; Zellmann, 2018). The engine noise model considers the *Mach* number as well as the engine rotational speed *N1* at every point of the trajectory. The airframe noise model considers the *Mach* number and air density at flight altitude along with settings of flaps, speedbrakes and landing gears. This allows the simulation of specific approach procedures such as CDA and enables the reproduction of effects generated by LNAS.

Both partial emission models were established from an extensive empirical dataset (Zellmann et al., 2017; Zellmann, 2018). The sound propagation is calculated with a sophisticated propagation model (Wunderli et al., 2018). The entire simulation chain is formulated for one-third octave bands ranging from 25 Hz to 5 kHz (Wunderli et al., 2018; Zellmann et al., 2017; Zellmann, 2018). The suitability of sonAIR for single flight simulations was demonstrated in an extensive validation (Jäger et al., 2021).

2.3.1. Input data

Terrain was represented by a raster with 25 m resolution. It was composed from the 2018 swissALTI3D (swisstopo) for Switzerland and from the 2016 Copernicus EU-DEM (Copernicus) for Germany.

Ground cover was also represented by a 25 m raster. It was composed from the swissTLM3D (swisstopo) for Switzerland and from Copernicus CORINE Land Cover (Copernicus, 2018) for Germany. Ground cover data is used in the propagation simulation to calculate ground reflections.

The simulations were done under the assumption of a homogenous atmosphere. This is a sufficiently accurate assumption for the relatively short propagation distances of between 350 and 800 m occurring in this analysis. Mean atmospheric conditions over all ATRA flights were used to define the homogenous atmosphere, namely, temperature $T = 16\ ^\circ C$, air pressure $p = 973$ hPa, and relative humidity $rH = 67\%$.

The flight trajectories were provided by DLR in the form of detailed FDR data. In order to use this data, a coordinate transformation from the World Geodetic System WGS84 to the Swiss grid CH1903 + and a spline of the trajectories to a time step resolution of 0.2

seconds was necessary. Additionally, the time of landing gear extension was shifted by + 8.9 seconds. This was necessary as the flag "gears down" in the FDR data represented the time when the gear lever was set. This was followed by the actual extension phase of the landing gears which on average lasted 17.8 seconds. Since sonAIR only features values for "gears in" and "gears out", the extension phase was split in half and distributed to these two categories.

2.3.2. Emission model

As already mentioned, sonAIR simulates noise emission separately for engine and airframe noise. Since different engines exhibit different acoustic emission characteristics, sonAIR models are not just defined for each individual airplane type, but for each engine variant as well.

The ATRA is an Airbus A320 with engine type IAE V2500. This combination is only available in sonAIR with the simplified airframe noise model A32X_V2500 that cannot account for the aircraft configuration (so-called reduced model), as no FDR data was available for the model generation (details see Zellmann et al., 2017). Since the working principle of LNAS is partly based on precise implementation of aircraft configuration, this model cannot simulate the ATRA flights with sufficient accuracy. sonAIR features another A320 emission model with full configuration capabilities (so-called advanced model (Zellmann et al., 2017), but this is based on the aircraft version with engine type CFM56-5B (model A320_CFM56-5B). A hybrid model was therefore generated for ATRA by combining the airframe model from A320_CFM56-5B with the engine model from A32X_V2500.

Since sonAIR models are based on real overflight measurements, airframe and engine noise was separated empirically (Zellmann et al., 2017), potentially leaving residual engine noise contribution in the airframe model and vice versa. This could introduce additional uncertainty when combining engine and airframe models that are based on separate measurements. Such combination has not been tested in sonAIR before, therefore the hybrid model had to be validated before further use (see Sections 3.2.1 and 4.2.1). Successful implementation of this hybrid approach also opens up new applications for sonAIR, as it allows the simulation of non-existent aircraft-engine combinations.

2.3.3. Noise map generation

Each ATRA flight was simulated individually using the service tool of sonAIR which is integrated into a geographic information system (GIS) (Wunderli et al., 2018). Sound exposure levels were calculated for a receiver grid with a mesh size of 150 meters and receiver height over ground of four meters. Based on this grid, noise footprints were calculated for each individual ATRA flight and then energetically averaged for the two flight groups (with/without LNAS). In addition, the sound exposure levels at the exact positions and heights of the six measurement stations were calculated for direct comparison with the measurements.

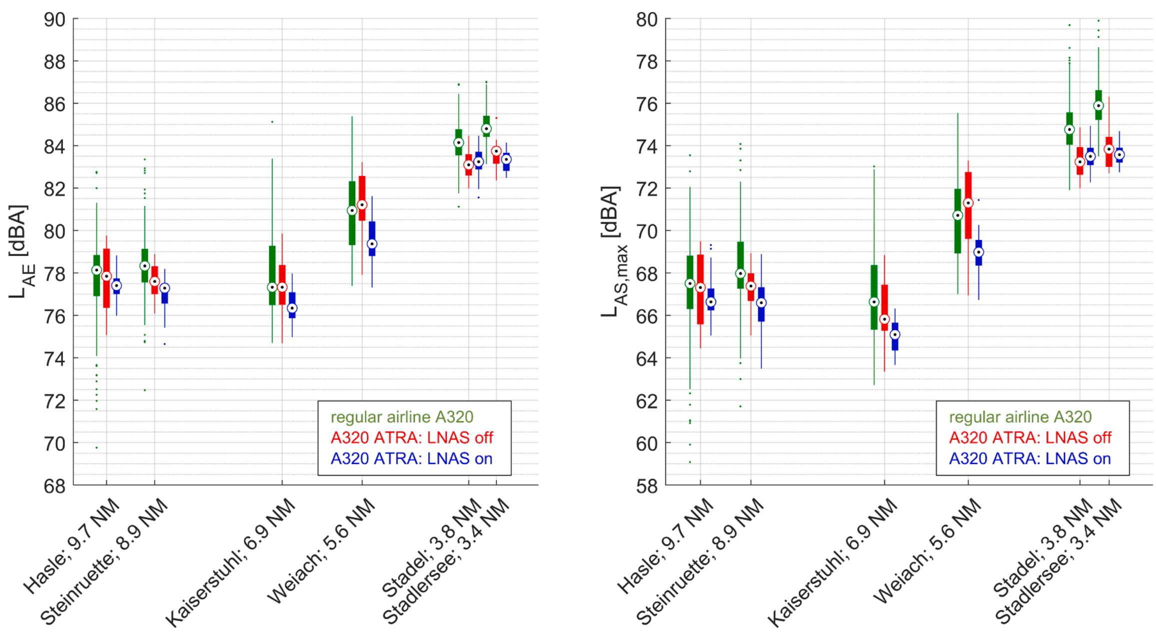

Fig. 3. Box-whisker-plots of measured sound exposure levels L_{AE} (left) and maximum levels $L_{AS,max}$ (right), separated by measurement position (including distance to touchdown in nautical miles (NM)) and flight group. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

3. Results

3.1. Measurements

The acoustical evaluation of the 64 valid and representative ATRA approaches was done individually for each measurement position (MP) by combining the measurements into groups for ATRA-flights with LNAS (43 approaches) and ATRA-flights without LNAS (21 approaches). In addition, 158 regular approaches performed by the A320 fleet of one airline operating from Zurich Airport during the test week were evaluated for direct comparison. Fig. 3 displays the measurements for each MP as box-whisker-plots, separated into these three groups.

The box-whisker-plots display the median value as center point of each box. In addition, the energetic mean was calculated for all groups, as the latter is used in acoustics as the basis for calculating long-term noise averages. Due to the logarithmic scale, energetic means are typically slightly higher than the median. Table 1 contains the energetically averaged sound exposure levels L_{AE} with corresponding standard deviations and the number of samples for the three flight groups at every MP. Additionally, the differences between ATRA flights with and without LNAS as well as between regular airline A320 flights and ATRA flights with LNAS are listed. The corresponding standard deviations were calculated according to the laws of error propagation.

The approaches performed with LNAS produced lower average noise levels at five of the six MPs compared to the flights without LNAS. The reduction is more pronounced in the maximum level (reduction of mean $L_{AS,max}$ up to 2.4 dBA) than in the sound exposure level (reduction of average L_{AE} up to 1.8 dBA). The largest effect was found in the area where the landing gears are typically extracted (transition area), represented by MPs *Kaiserstuhl* and *Weiach*. At MP *Stadel*, a negligible level increase of 0.1 dBA was observed.

Aside from the overall reduction, the results also indicate that the variation of noise levels between individual flights is smaller in the *LNAS on* group. At every MP, the loudest flights both in terms of L_{AE} and $L_{AS,max}$ were observed in the group without LNAS. At three of the six MPs, the lowest values were also produced without LNAS, albeit by three different flights. Therefore these low values can be attributed to the generally larger measurement scattering of approaches without LNAS, which can produce outliers in both directions.

The regular airline A320 approaches displayed consistently higher average noise levels at all MPs compared to the ATRA flights with LNAS, with maximum differences again observed at MPs *Kaiserstuhl* and *Weiach*. When compared to ATRA flights without LNAS, the regular airline approaches produced similar average levels at MPs *Hasle*, *Kaiserstuhl* and *Weiach*, but higher levels at the other MPs. The variation between lowest and highest noise levels of the regular airline A320 approaches is much larger than that observed from the ATRA flights. It has to be noted that comparability between the measured regular approaches and ATRA approaches is lower than between the ATRA approaches, since the lack of flight track data prevented an exclusion of atypical approaches before analysis (see Section 4.1.2).

3.2. Simulation

3.2.1. Comparison with measurements

As we used a hybrid emission model for ATRA combined from two A320 versions (see Section 2.3.2), we validated this model by comparing the simulated noise levels at every MP with the measurements. Fig. 4 shows the difference between simulated and measured levels at each MP individually as box-whisker-plots for the flights with and without LNAS.

The simulations generally agreed well with the measurements, with a mean deviation of sound exposure levels over all measurement locations of $\Delta L_{AE} = -0.1 \pm 0.8$ dBA for approaches with LNAS and $\Delta L_{AE} = -0.3 \pm 1.0$ dBA for approaches without LNAS. A general trend toward underestimation by roughly one decibel was observed at MP *Hasle* for L_{AE} and $L_{AS,max}$ and also at *Steinruette* for $L_{AS,max}$. Additionally, flights without LNAS were underestimated by roughly one decibel at MP *Weiach* in both L_{AE} and $L_{AS,max}$.

Table 1
Energetically averaged sound exposure levels L_{AE} with standard deviations from measurements for the three flight groups "ATRA: LNAS on", "ATRA: LNAS off" and "regular airline A320″ for each MP. n gives the number of samples per group. Additionally, the difference between the groups "ATRA: LNAS off" and "ATRA: LNAS on" as well as between "ATRA: LNAS on" and "regular airline A320″ are listed with corresponding standard deviations.

MP	L_{AE} ATRA: LNAS on	L_{AE} ATRA: LNAS off	L_{AE} regular airline	ΔL_{AE} LNAS off/on	ΔL_{AE} regular/LNAS on
Hasle	77.4 ± 0.6 dBA (n = 43)	77.8 ± 1.5 dBA (n = 20)	78.1 ± 2.1 dBA (n = 148)	0.4 ± 1.6 dBA	0.7 ± 2.2 dBA
Steinruette	77.3 ± 0.8 dBA (n = 42)	77.6 ± 0.8 dBA (n = 21)	78.3 ± 1.6 dBA (n = 142)	0.3 ± 1.2 dBA	1.0 ± 1.8 dBA
Kaiserstuhl	76.3 ± 0.8 dBA (n = 41)	77.3 ± 1.4 dBA (n = 21)	77.3 ± 1.9 dBA (n = 149)	1.0 ± 1.6 dBA	1.0 ± 2.1 dBA
Weiach	79.4 ± 1.0 dBA (n = 42)	81.2 ± 1.6 dBA (n = 21)	80.9 ± 1.8 dBA (n = 143)	1.8 ± 1.9 dBA	1.6 ± 2.1 dBA
Stadel	83.2 ± 0.6 dBA (n = 43)	83.1 ± 0.7 dBA (n = 21)	84.1 ± 1.0 dBA (n = 145)	−0.1 ± 0.9 dBA	0.9 ± 1.1 dBA
Stadlersee	83.4 ± 0.5 dBA (n = 40)	83.7 ± 0.7 dBA (n = 20)	84.8 ± 0.8 dBA (n = 148)	0.4 ± 0.8 dBA	1.4 ± 0.9 dBA

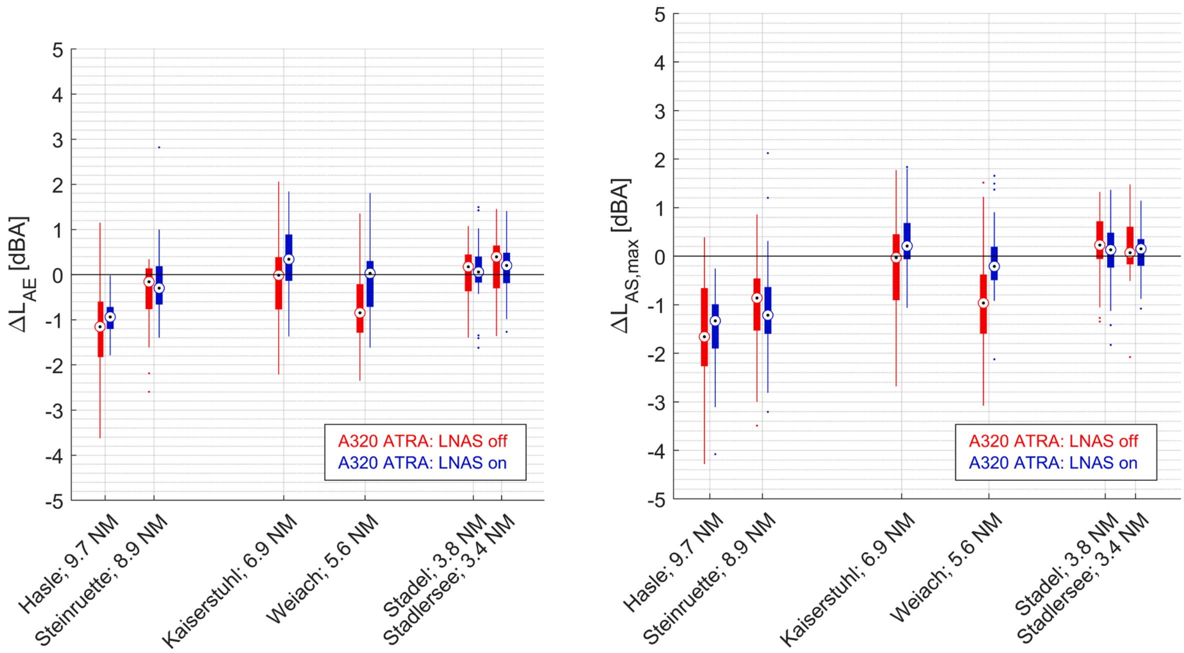

Fig. 4. Box-whisker-plots displaying the difference simulated minus measured sound exposure levels (left) and maximum levels (right) for each MP, individually for the ATRA flights with and without LNAS. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

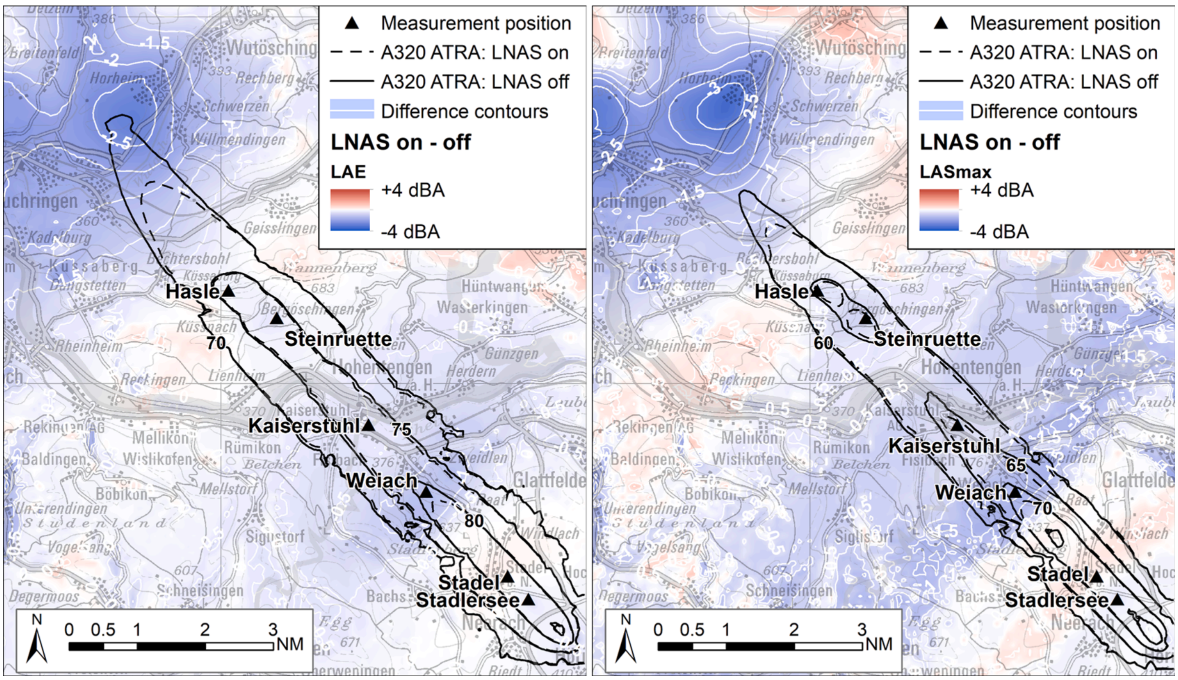

Fig. 5. Differences between energetically averaged L_{AE}-footprints (left) and $L_{AS,max}$-footprints (right) of ATRA flights with and without LNAS, symbolized with color shading (blue: noise reduction by LNAS; red: noise increase), with white contour lines in 0.5 dBA steps. Additionally, the absolute noise contours for 70 dBA, 75 dBA and 80 dBA (for L_{AE}) respective 60 dBA, 65 dBA and 70 dBA (for $L_{AS,max}$) are given for flights with LNAS (dashed black line) and without LNAS (solid black line). Map source: Federal Office of Topography. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

3.2.2. Noise maps

Fig. 5 displays the difference between the averaged noise footprints for flights with and without LNAS for the L_{AE} and $L_{AS,max}$.

The footprint difference maps show that the noise reductions observed in the measurements can largely be transferred to the laterally adjacent areas. All areas within the 70 dBA L_{AE} contour experienced either a clear level reduction or no significant level change when LNAS was used. Outside the 70 dBA contours, some areas lateral to MP *Hasle* experienced a slight increase in L_{AE}. The largest effect with reductions in L_{AE} of up to 2.5 dBA was observed in an area north of the measurement chain, roughly 13 nautical miles from the runway threshold.

The $L_{AS,max}$ footprint shows the same overall trends as the L_{AE}, but the effects were more pronounced. A reduction of around 1.5 dBA could be observed around *Weiach*, while the additional reduction area north of the measurement chain featured reductions of up to 3 dBA. The noise increase in areas laterally adjacent to measurement position *Hasle* affected larger areas than observed in the L_{AE}, with maximum increase in $L_{AS,max}$ of roughly 0.5 dBA. An additional area of slightly increased $L_{AS,max}$ was observed around MP *Stadel*.

4. Discussion

Measurements and simulated noise footprints confirm the considerable noise reduction potential of LNAS. During final approach, sound exposure levels could be reduced by up to 1.8 dBA, which is equivalent to a reduction of the number of overflights by roughly one third. In an area further from touchdown, where the airplanes turn into final approach, reductions in sound exposure levels of up to 2.5 dBA were observed, which energetically corresponds to over 40% reduction in the number of overflights. Additionally, particularly loud single events were successfully eliminated. In the following subsections, these findings are discussed in more detail.

4.1. Measurements

4.1.1. Comparison of ATRA flight groups

Direct comparison of measurements from ATRA flights show that LNAS achieved a reduction in sound exposure levels at five of the six measurement positions. The largest reduction in measured levels was observed in the transition area between five and seven nautical miles from touchdown (MPs *Kaiserstuhl* and *Weiach*). Thanks to lower airspeeds and optimized configuration timing (especially later gear extraction at lower speeds), LNAS reduced the energetically averaged L_{AE} by up to 1.8 dBA compared to the non-LNAS approaches.

At the furthest MPs *Hasle* and *Steinruette*, 9.7 resp. 8.9 nautical miles from touchdown, a reduction in L_{AE} of roughly half a dBA was observed. This reduction was mainly achieved by a higher average flight altitude when LNAS was used (see Fig. 6).

In the close range (three to four nautical miles from touchdown; MPs *Stadel* and *Stadlersee*), little differences between the flight groups were observed. This was expected, since all flights needed to be fully configured for landing around these distances. Therefore

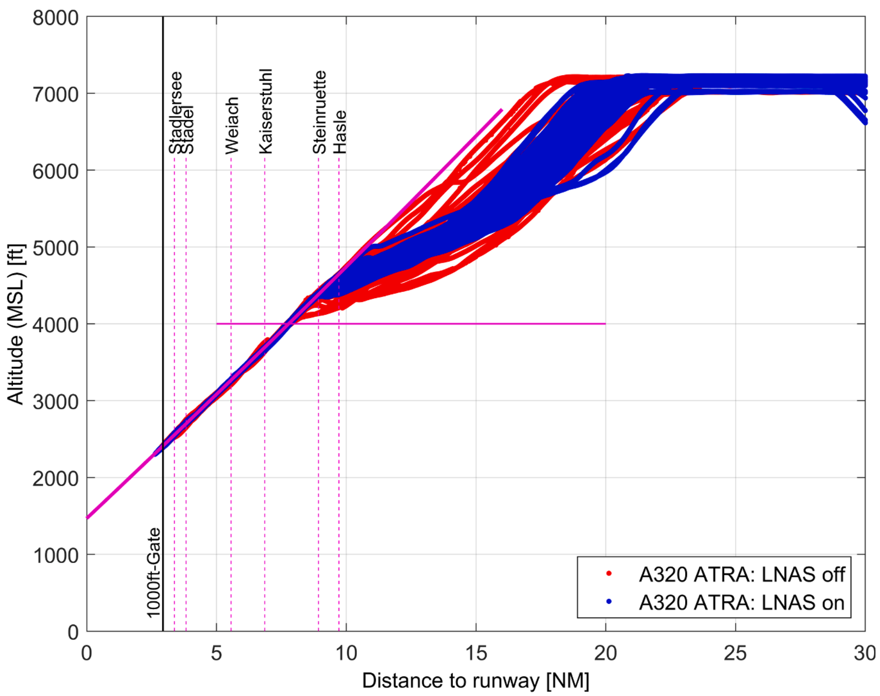

Fig. 6. Vertical profiles of ATRA flights (blue: LNAS on/red: LNAS off). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

LNAS could not achieve any further noise reduction.

4.1.2. Comparison ATRA vs. regular airline flights

When comparing the ATRA flights with the regular airline A320 flights, we have to take into account that the data quality of the regular airline measurements is poorer due to the lack of flight track data. No sorting by approach procedure could therefore be done. While the observed airline by default flies CDA toward Zurich airport, it cannot be ruled out that a small percentage of measured approaches were flown using the LDLP approach procedure, which might increase the measured levels at MPs *Hasle* and *Steinruette* due to lower overflight altitudes.

After passing *Steinruette*, all approaches have to follow the preset glide slope regardless of the chosen approach procedure, therefore measurements at the subsequent four MPs should be comparable with ATRA measurements. Despite this, the regular airline A320 flights displayed average noise exposure levels at MPs *Stadel* and *Stadlersee* that were around 1 dBA higher than the ATRA counterparts. This discrepancy can be explained by the engine type: the regular airline A320 fleet measured for this comparison had the CFM56-5B engine installed which is 1.2 dB louder than the IAE V2500 installed on the ATRA, according to certification measurements (ECAC, 2016). In the early part of the glide path, engines were mostly in idle, therefore the engine noise did not substantially contribute to the total noise. However, from the stabilization distance of four nautical miles from touchdown onwards, the engine power is typically increased. As a consequence, the louder engine type generated higher total L_{AE} compared to ATRA.

At MPs *Kaiserstuhl* and *Weiach,* neither differing approach procedures nor different engine types influenced the comparison. At these locations, measurements of regular airline A320 approaches showed comparable levels to the ATRA approaches without LNAS. Based on this, we regard the ATRA flights without LNAS as an accurate baseline for the comparison of mean noise levels for CDA.

4.1.3. Noise outliers

Aside from the overall noise exposure, residents in the approach sector are particularly affected by single, exceptionally loud approaches. These are likely to attract more attention and therefore increase long-term annoyance (De Coensel et al., 2009) and are particularly linked to higher probabilities of awakening reactions (e.g. Basner et al., 2006). LNAS is well suited to avoid such loud events, as can be seen by comparing the loudest single flights between the groups *LNAS on* and *LNAS off*. The largest difference could be observed at MP *Kaiserstuhl*, with the highest measured $L_{AS,max}$ being 2.5 dBA lower in the group with LNAS compared to the group without LNAS.

The measured levels of the regular airline A320 approaches scattered more prominently and displayed more pronounced noise outliers than those of ATRA approaches. This increased scattering cannot be explained by atmospheric differences, since the regular airline A320 were measured during the same time period and therefore under the same atmospheric conditions as the ATRA flights. At MPs *Hasle* and *Steinruette*, the increased scattering might partly be due to the presence of a few non-CDAs in the dataset (see Section 4.1.2). However, we suspect the main reason of this difference in scattering to be an observation effect: the artificial test environment might have led pilots flying the ATRA to spend more attention than usual to optimal energy balance, even without the help of LNAS. Regular airline approaches, on the other hand, likely feature more pronounced variability in engine thrust and airplane configuration, which are the main cause for noise variability within approaches of the same aircraft type (Snellen et al., 2017). As a consequence, it is not unreasonable to assume that the outlier reduction potential of LNAS is larger than what the comparison between ATRA flights with and without LNAS suggested. Our measurements indicate differences between loudest regular airline A320 approach and loudest ATRA approach using LNAS of more than 5 dBA (see Fig. 3). However, no FDR data was available for further analysis of the regular airline approaches, therefore we could not identify the root cause of this difference. Regardless of a detailed explanation of this finding, a considerable potential of LNAS to reduce long-term annoyance and awakening reactions through outlier reduction can be stated.

4.2. Simulation

4.2.1. Comparison with measurements

The comparison between simulations and measurements revealed very good agreement at four of six measurement locations (see Fig. 4). At MP *Hasle*, a slight underestimation of around 1 dBA was found. The fact that flights with and without LNAS were equally underestimated suggests a propagation phenomenon as likely cause. The microphone at *Hasle* was installed right next to a gravel road which can be characterized as acoustically fully reflective. Due to the lower level of detail of the land cover data for Germany, this road was not included in the simulation. Instead, the entire surroundings of MP *Hasle* was modelled as grassland, leading to an underestimation of ground reflectance. Sensitivity tests on ground cover in sonAIR simulations show differences in ground reflectance between grassland and fully reflective surfaces of roughly 1 dBA at a receiver height of four meters, therefore the lower level of detail of the land cover data is a plausible explanation for the underestimation of the simulated sound exposure levels.

At MP *Weiach*, flights without LNAS were underestimated by roughly 1 dBA, while flights with LNAS were reproduced accurately. A closer investigation of the FDR data at this location revealed a negative correlation between the true airspeed (TAS) and the agreement between simulation and measurement: simulations of slower flights showed a tendency towards an overestimation while faster flights were underestimated. The sonAIR emission models were established using the ground speed (GS) instead of TAS. This is advantageous insofar as GS is always available as input since it can be extracted from radar data, while TAS is only obtained from FDR data. On the flipside, this introduces additional uncertainty since effects of head- or tailwind are not considered. Additionally, the models were somewhat simplified by decoupling the input velocity from the flaps settings and omitting the angle of attack (AoA) as input parameter (see Zellmann et al., 2017; Zellmann, 2018). The cumulative effect is that approaches without LNAS were underestimated since they show higher average airspeeds at MP *Weiach* than approaches with LNAS. Inclusion of TAS and AoA as input parameters in the model might increase the simulation accuracy in the transition area. However, such emission model extensions were beyond the scope of this study.

Despite the slight underestimations in *Hasle* and *Weiach*, the overall agreement between simulations and measurements was very good, with differences in L_{AE} of below 0.5 dBA and standard deviations below 1 dBA. This good result despite the use of a hybrid model produced from two separate emission models confirmed that the separation of engine and airframe noise in sonAIR works accurately. It also confirmed that the simulations were suitable to assess the noise reduction potential of LNAS via noise maps.

4.2.2. Noise maps

The simulated footprints showed a reduction of the sound exposure levels on the ground within the 70 dBA noise contour along the entire glide path up to around four nautical miles before touchdown (stabilization distance). The beneficial effect was visible directly underneath the flight path as well as to the side.

Within the last four miles before touchdown, no further reduction was observed. However, a large noise reduction potential was found in the area beyond ten nautical miles from touchdown, where measurements were not feasible due to bad signal-to-noise ratio at ground level. Detailed analysis of FDR data revealed that this noise reduction was achieved by lower average airspeeds and later extraction of the first flap stage.

The noise maps underestimated the reduction potential of LNAS in the transition area around MP *Weiach* by roughly 1 dBA. This was due to a tendency of sonAIR toward underestimation of the faster approaches without LNAS in the transition area (see Sections 3.2.1 and 4.2.1).

Outside the 70 dBA contour, some areas lateral to MP *Hasle* experienced a slight increase in sound exposure levels due to LNAS. This is an effect of the higher average overflight height over MPs *Hasle* and *Steinruette* when LNAS was used (see Fig. 6). While the higher altitude led to lower sound exposure levels directly underneath the flightpath, it also caused steeper sound propagation angles toward areas lateral of the flight path. This decreased lateral and foliage attenuation effects and consequently slightly increased simulated sound exposure levels. However, this increase was small, limited to areas outside the 70 dBA contour and primarily present in forested areas. Therefore, the adverse effect for residents is minimal and is far outweighed by the noise reduction achieved by LNAS in all other areas.

5. Conclusion

The Low Noise Augmentation System (LNAS) is a pilot assistance system supporting pilots in optimizing approaches in terms of fuel consumption and noise emission. A flight test campaign with focus on continuous descent approaches, conducted with an Airbus A320 at Zurich Airport, Switzerland, revealed noise reductions of up to 1.8 dBA in terms of sound exposure levels. Such reduction is energetically equivalent to a reduction in the number of overflights by roughly one third. Additionally, LNAS was found to be effective in eliminating particularly loud single events. Measurements indicated the largest reduction potential in the transition area where landing gears are extracted (between five and seven nautical miles from touchdown).

Simulation of noise footprints using the aircraft noise simulation model sonAIR confirmed these findings and indicated that the measured noise reductions can largely be transferred to laterally adjacent areas. Furthermore, an area with prominent noise reduction of up to 2.5 dBA in terms of sound exposure levels was identified in the far range at distances of roughly 13 nautical miles from touchdown. This is energetically equivalent to a reduction of the number of overflights in this area by more than 40%.

Our findings confirm that LNAS is an effective tool to mitigate aircraft noise and long-term noise annoyance in the approach sector with minimal interference in the aircraft infrastructure or operational flight procedures. In future work, it would be interesting to investigate whether the observed reduction in sound pressure metrics could also be observed in sound quality metrics which are better suited to describe short-term annoyance of aircraft noise (Merino-Martinez et al., 2019).

As a next development step, LNAS is currently undergoing operational flight tests on a fleet of 150 Airbus A320 aircraft. The goal of this test is to evaluate LNAS over at least 1000 approaches toward Frankfurt Airport, Germany, within a 12 month period. Another operational test phase using the current software version supporting CDAs is in planning.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

We would like to thank Zurich Airport for their continued support throughout the project and Skyguide for coordinating the test flights within the framework of regular air traffic. The authors further thank the participating pilots for their time and positive commitment.

Funding

This work was financed by the Federal Office of Civil Aviation FOCA (Art. 87b BV); the Canton Zurich; and the Federal Office for the Environment FOEN. None of these sponsors were involved in the study design, data collection or analysis.

References

Abdelmoula, F., Scholz, M., 2018. LNAS – a pilot assistance system for low-noise approaches with minimal fuel consumption. In: 31st Congress of the International Council of the Aeronautical Sciences. Belo Horizonte, Brazil, pp. 9–14.

Basner, Mathias, Samel, Alexander, Isermann, Ullrich, 2006. Aircraft noise effects on sleep: application of the results of a large poly-somnographic field study. J. Acoust. Soc. Am. 119 (5), 2772–2784. https://doi.org/10.1121/1.2184247.

Copernicus. EU-DEM v1.1. https://land.copernicus.eu/imagery-in-situ/eu-dem/eu-dem-v1.1 (access 12.04.2021).

Copernicus. CLC 2018. https://land.copernicus.eu/pan-european/corine-land-cover/clc2018 (access 12.04.2021).

De Coensel, B., Botteldooren, D., De Muer, T., Berglund, B., Nilsson, M.E., Lercher, P., 2009. A model for the perception of environmental sound based on notice-events. J. Acoust. Soc. Am 126 (2), 656–665. https://doi.org/10.1121/1.3158601.

EASA, 2019. European Aviation Environmental Report 2019. https://doi.org/10.2822/309946.

ECAC, 2016. DOC.29: Report on Standard Method of Computing Noise Contours around Civil Airports, Volume 1: Applications Guide, 4th ed., Europ Civil Aviat Conf (ECAC), Neuilly-sur-Seine, France.

ICAO, 2008. Guidance on the Balanced Approach to Aircraft Noise Management. Doc 9829 AN/451. Montreal, Canada.

Jäger, D., Zellmann, C., Schlatter, F., Wunderli, J.M., 2021. Validation of the sonAIR aircraft noise simulation model. Noise Mapping 8 (1), 95–107. https://doi.org/10.1515/noise-2021-0007.

Kühne, C. G., Scholz, M., Abdelmoula, F., 2018. LNAS – a pilot assistance system for energy-optimal approaches using existing aircraft-infrastructure. AEGATS '18, Toulouse, France.

Merino-Martinez, R., Snellen, M., 2020. Implementation of tonal cavity noise estimations in landing gear noise prediction models. In: 26th AIAA/CEAS Aeroacoustics Conference, 15 - 19 June 2020. Online event. https://doi.org/10.2514/6.2020-2578.

Merino-Martinez, R., Bertsch, L., Simons, D., Snellen, M., 2016. Analysis of landing gear noise during approach. In: 22nd AIAA/CEAS Aeroacoustics Conference, 30 May - 1 June 2016. Lyon, France. https://doi.org/10.2514/6.2016-2769.

Merino-Martinez, R., Vieira, A., Snellen, M.G., Simons, D., 2019. Sound quality metrics applied to aircraft components under operational conditions using a microphone array. In: 25th AIAA/CEAS aeroacoustics conference, Delft, Netherlands. https://doi.org/10.2514/6.2019-2513.

NASA, 2020. Urban Air Mobility Noise: Current Practice, Gaps, and Recommendations. NASA/TP–2020-5007433. Hampton, Virginia.

Pereda Albarrán, M.Y., Sahai, A.K., Stumpf, E., 2017. Aircraft noise sound quality evaluation of continuous descent approaches. In: INTER-NOISE and NOISE-CON Congress and Conference Proceedings 255(5). Institute of Noise Control Engineering, pp. 2898–2909.

Scholz, M., Abdelmoula, F., 2017. Active noise abatement using the new developed pilot assistance system LNAS. In: INTER-NOISE and NOISE-CON Congress and Conference Proceedings 255(5). Institute of Noise Control Engineering, pp. 2678–2689.

Snellen, M., Merino-Martínez, R., Simons, D.G., 2017. Assessment of noise variability of landing aircraft using phased microphone array. J. Aircr. 54 (6), 2173–2183. https://doi.org/10.2514/1.C033950.

swisstopo. swissTLM3D. https://shop.swisstopo.admin.ch/en/products/landscape/tlm3D (access 12.04.2021).

swisstopo. swissALTI3D. https://www.swisstopo.admin.ch/en/geodata/height/alti3d.html (access 12.04.2021).

Wunderli, J.M., Zellmann, C., Köpfli, M., Habermacher, M., Schwab, O., Schlatter, F., Schäffer, B., 2018. sonAIR - a GIS-integrated spectral aircraft noise simulation tool for single flight prediction and noise mapping. Acta Acust United Ac. 104 (3), 440–451. https://doi.org/10.3813/AAA.919180.

Zellmann, C., Jäger, D., Schlatter, F., 2018. Model adjustment and validation to account for the airflow deflector retrofit of the A320 family. Euronoise '18, Crete, Greece.

Zellmann, C., Schäffer, B., Wunderli, J.M., Isermann, U., Paschereit, C.O., 2017. Aircraft noise emission model accounting for aircraft flight parameters. J. Aircr. 55 (2), 682–695. https://doi.org/10.2514/1.C034275.

Zellmann, C., 2018. Development of an Aircraft Noise Emission Model Accounting for Flight Parameters. PhD thesis. Technische Universität Berlin. Berlin, Germany.

Glossary

AoA: Angle of Attack
ATC: Air Traffic Control
ATRA: Advanced Technology Research Aircraft
CDA: Continuous Descend Approach procedure
DLR: German Aerospace Center
FDR: Flight Data Recorder
GS: Ground Speed
L_{AE}: A-weighted sound exposure level
$L_{AS,max}$: A-weighted maximum level, based on level-time histories smoothed with one second moving window
LDLP: Low Drag Low Power approach procedure
LNAS: Low Noise Augmentation System
MP: Measurement Position
TAS: True Airspeed
WGS84: World Geodetic System 1984