Aircraft Noise Modeling of Departure Flight Events based on Radar Tracks and Actual Aircraft Performance Parameters

Christoph Strümpfel, Josephin Hübner

Technische Universität Berlin, Institut für Luft- und Raumfahrt, Fachgebiet Flugführung und Luftverkehr, 10587 Berlin, E-Mail: christoph.struempfel@tu-berlin.de

Introduction

Residents living in the vicinity of airports suffer from noise pollution caused by aircraft. Recent technical and operational improvements in active noise abatement have led to a 14 % reduction in average noise energy per flight between 2005 and 2017 (calculated on the basis of certified noise levels in EPNdB for each aircraft type). However, as the number of revenue passenger kilometers has increased by 60 % over the same period, the positive trend resulting from improvements in individual flights is not apparent to airport communities: Since 2005, the number of people affected within the L_{DEN} 55 dB noise contours of 47 major airports in Europe has increased by 14 % to 2.58 million [1]. Since the proportion of residents who are highly annoyed (%HA) by aircraft noise is higher than that caused by rail or road noise [2] an in-depth analysis of the current aircraft noise exposure around airports is necessary. Hereinafter, operational noise abatement measures (e.g. noise abatement departure procedures, NADP) can be applied, which allow an improvement of the aircraft noise situation at airports in a comparable short time.

The actual aircraft noise situation in airport surroundings can be assessed by analyzing noise measurement data. Because the number of measurement points is limited, the conclusion on other significant points besides the measurement points is limited. Alternatively, the noise exposure contours from air traffic can be calculated entirely. However, the validity of the calculated noise exposure is highly depended on the input dataset, such as flight trajectories, aircraft performance data, source emission characteristics, flight operational and procedural data and meteorological data.

Therefore, the aim of this paper is i) to provide a methodology to calculate actual aircraft performance parameters (e.g. mass, thrust, flap setting) from basic radar 4D-trajectory data of single departure flights and ii) compare the noise data from measurement points with calculated noise data based on the enhanced radar data and using the ECAC Doc 29 4th noise model (incorporated in the Aviation Environmental Design Tool, AEDT).

Background

Since flight trajectory data is available for the majority of operated civil flights (e.g. via ADS-B) new opportunities arise with regard to reverse engineering of flight and aircraft specific performance parameters. Calculating aircraft mass and engine thrust along the trajectory facilitate environmental assessment studies: In the aircraft noise model such as described in ECAC Doc 29 the calculated noise at any reception point follows a Noise-Power-Distance (NPD) relationship, which is a function of the engine thrust setting, the slant distance between reception point and aircraft position, and the aircraft type specific characteristics, laid down in the EUROCONTROL Aircraft Noise and Performance Database (ANP) [3]. The engine thrust is mandatory for the fuel flow calculation, which in turn enables aircraft mass progress and engine emissions calculations. When using a simplified point-mass-model to describe the aircraft's state the forces acting on the aircraft (lift, drag, gravity and thrust) are inter alia directly dependent on the aircraft mass.

In [4], data from aircraft flight data recorders (FDR) were taken to validate calculated speeds, flap settings and engine thrust calculated from radar data. However, it remains unclear how weather data and flight operational data was included in the algorithm. Other previous studies used the initial climb phase to estimate the aircraft mass from trajectory data and validated the results with the EUROCONTROL Base of Aircraft Data (BADA) (total energy model) and other performance models, but not real flight operational data [5][6]. Earlier research studies by the author enhanced this methodology by implementing assumed flight procedures [7]. In this paper the results for the validation of the algorithm with flight operational data of departure flights are presented.

Depending on the degree of processing effort and depth of detail we distinguish the input dataset for noise calculation of departure flights between three level of detail (low to high):

a. Lateral track data with standard vertical profiles
b. Lateral track data with standard vertical profiles and actual takeoff mass and initial thrust setting.
c. 4D-trajectory data (3D + time) plus actual aircraft mass, engine thrust and true airspeed along the trajectory.

Whereas in a) and b) standard vertical profiles from the ANP can be used c) requires extensive processing of the radar data to estimate aircraft performance. To minimize the differences between calculated and measured noise levels the actual aircraft mass and ANP NPD data can be identified as the most important factors that can lead into differences between calculated and measured levels [8].

This study utilizes radar data, operational flight data and noise measurement data, which was originally used to assess noise abatement procedures at Berlin-Tegel airport. Here, we applied our methods for performance parameter estimation and noise calculation based on radar tracks to determine a realistic number of affected residents within certain noise exposure contours. [9]

Methods

In this section, we provide the framework for aircraft performance calculation based on radar data, including the required input data and necessary data processing. We outline the validation process for aircraft mass, thrust and the comparison of calculated and measured noise exposure levels.

Input data

For this study, radar data from the German Air Navigation Service Provider DFS were used. The data base is provided in the FANOMOS format and contains for each trajectory point: the aircraft position in 3D, time (0.25 Hz resolution, since start of data recording), ground speed and cumulative track distance as well as operational data about the used runway, actual takeoff time, aircraft type and flight number. The vertical accuracy is stated as +/- 100 ft and lateral accuracy +/- 200 m (in turns max. +/- 400 m). The takeoff run phase is not provided, as the trajectory usually starts at around 150-250 ft AGL earliest.

Radar data forms the core of the input data and is the minimum of required flight-specific trajectory data. Using ADS-B data instead offers higher 4D resolution, avionics-equipment dependent higher position accuracy and often includes the takeoff run segment.

Data processing

Our approach to estimate the aircraft mass and engine thrust along the full trajectory can be viewed in Fig. 1.

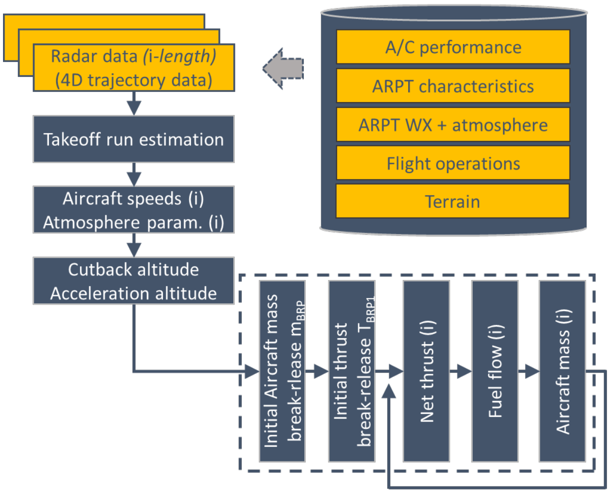

Fig. 1: Aircraft mass and thrust estimation algorithm

First, the takeoff run phase is estimated. This is done by intersecting the initial climb vector with the airport terrain surface by means of a linear regression. Flight operational assumptions about the takeoff run phase (rotation angular speed, initial pitch target, rotation speed and line-up distance before break release) facilitate a realistic description of the takeoff run from break-release point (BRP) upon lift-off and start of the radar trajectory.

Second, the core dataset is enhanced by atmosphere data for each trajectory point, which is required for the aircraft performance calculation: Static outside air temperature, static pressure, density, humidity, wind direction and speed. The weather model is based on airport weather data, atmosphere measurements from the Lindenberg Meteorological observatory of the German weather service DWD and MERRA2 data from the NASA Global Modeling and Assimilation Office. The derivation of weather parameters along the flight trajectory also allows the calculation of flight speeds besides the ground speed [10]: Calibrated airspeed (CAS, relevant for the calculation of flap speeds, acceleration altitude and takeoff safety speed V_2) and true airspeed (TAS, relevant for flight mechanic and aerodynamic calculations).

Third, the estimation of the thrust reduction (cutback) and acceleration altitude is important, if the procedural profiles in the ANP shall be modified to fit the specific trajectory. We estimated the cutback altitude analyzing the flight path angle progress (first local maximum) and the acceleration altitude based on calibrated airspeed progress (first local minimum) with an overall accuracy of 82 %. This makes it possible to identify the NADP that was operated during departure.

Aircraft performance parameter estimation

The aircraft mass and thrust at the BRP is initially estimated based in part on previous research work by the authors [7]. We assume that the aircraft targets the takeoff safety speed V_2+10 kt until reaching the cutback altitude [11], which can be retrieved from the calculated CAS during climb out. Applying EASA CS-25 25.107, the aircraft mass based on V_2 can be calculated as follows:

$$m_{V2} = \frac{(V_2)^2 \cdot \rho \cdot S \cdot C_{L,MAX,1+F}}{1{,}13^2 \cdot 2 \cdot g} \qquad (1)$$

where g is the acceleration due to gravity (latitude-dependent), $C_{L,MAX,1+F}$ is the maximum lift coefficient for takeoff flap setting 1+F (assumes 1+F as the standard flap setting for A320 during takeoff), S is the wing reference surface and ρ is the air density at field elevation.

Knowing the aircraft mass for the initial climb out phase we calculate, in two iterations, the required gross thrust T_{BRP} to accelerate the aircraft along the runway:

$$T_{BRP0} = m_{v2} \cdot a + D + F_f \text{ with } F_f = \mu\,(G - L), \qquad (2)$$

where a is the rate of acceleration during takeoff run and D is the total drag force. F_f is the friction force and can calculated along the takeoff run using gravity force, lift force and the friction coefficient. For the calculation of drag (and lift) BADA aircraft performance coefficients are used.

With T_{BRP0} we apply the BADA fuel consumption model [10] to calculate the fuel burn until lift-off and add this amount to m_{v2}, which gives us m_{BRP}, thus the takeoff aircraft mass. Now, the actual T_{BRP1} can be calculated using (2).

In this paper, we calculate the aircraft thrust along the trajectory according the BADA BEAM model. Here, the net thrust T_{net} along the trajectory is calculated using T_{BRP1} with BEAM coefficients for current true airspeed, altitude and temperature deviation from ISA. Based on the calculated thrust, fuel consumption and the aircraft mass progress is then calculated along the trajectory. [12]

Validation data - flight operational data

For the validation of the algorithm for aircraft performance parameter estimation, flight operational data was provided for 13 postal flights (Aircraft type Airbus A319-112) [9]. Besides the takeoff mass and engine flex temperature setting (reduced thrust setting for takeoff) also takeoff procedures, NADP and flap setting were available.

With the provided flex temperature (assumed engine thrust for any assumed temperature at actual outside conditions) we can calculate the reduced thrust force per engine T_{Flex}:

$$T_{Flex} = T_{\max} \cdot \left(\frac{1 - 0.00273 \cdot t_{flex}}{1 - 0.00273 \cdot 86}\right) + K_{alt} + K_{alt,sq} + K_{temp} \quad (3)$$

where T_{max} is the maximum engine thrust at sea level and ISA conditions and t_{flex} is the assumed temperature [°F]. The correction factors for airport elevation K_{alt}, $K_{alt,sq}$ and outside air temperature K_{temp} are based on the ANP. [13]

Validation data – noise measurement data

Noise measurement data for all affected noise measurement points (MP) along the departure track were provided for all flights. In this study, we used the $L_{AS,MAX}$ only to validate the calculated noise exposure. Future research will use additional parameters for validation, such as 10 dB-down-time (t10) and the elevation angle between receptor and aircraft.

Noise calculation acc. ECAC Doc 29 4th Ed.

AEDT (version 3c) is used for validation and comparison between calculated and measured noise exposure and the underlying noise model implemented in AEDT correspond to ECAC Doc 29 4th Ed. [3][13]. We model the trajectory in AEDT in three variations:

I. Track data and ANP procedural profiles ICAO A/B (equal to NADP1/2), but calculated m_{BRP} and T_{BRP1} as initial input (*Procedural Profile – Standard*)

II. Modified procedural profiles with similar speed and altitude segment step types like the radar trajectory, and m_{BRP} and T_{BRP1} as initial input. (*Procedural Profile – Advanced*)

III. *Fixed point profiles*, providing the 3D radar trajectory as well as TAS and T_{net} for each trajectory point.

Results

Fig. 2 shows the radar tracks for all 13 departure flights and the position of the measurement points. 5 flights were operated as NADP2 procedures (cutback and acceleration at 1000 ft) and 8 flights as NADP1 procedures with varying acceleration altitude of 2000 and 3000 ft.

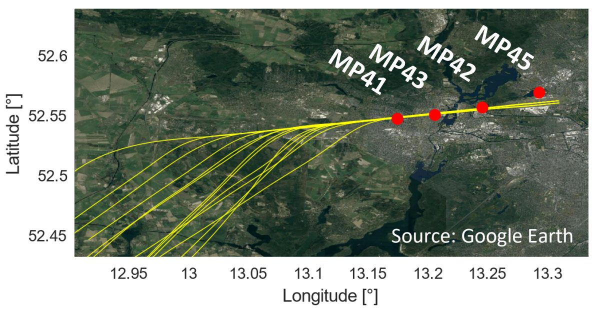

Fig. 2: Departure radar tracks and noise measurement points.

Validation of aircraft performance parameter estimation

Fig. 3 shows the deviation of takeoff mass and thrust as a boxplot. The mean absolute deviation (R) between calculated and operational takeoff mass is 3.100 kg (5.5 %), with a root mean square error (RMSE) of 460 kg. The strong deviations (marked as red crosses) might be due to inaccurate wind speed estimation during initial climb, which leads to an under-/overestimation of the true airspeed (main impact in eq. 1).

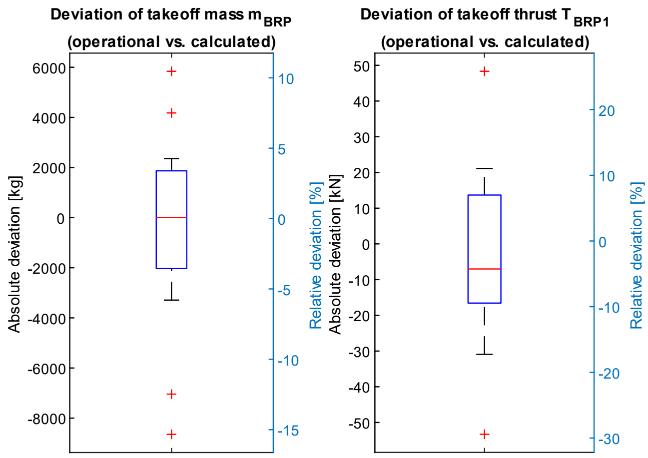

Fig. 3: Deviation of takeoff mass (left) and takeoff thrust (right)

The mean absolute deviation between calculated and operational takeoff thrust (at the BRP; sum of both engines) is 19.8 kN (11 %), with an RMSE of 3.8 kN. The algorithm tends to slightly underestimate the thrust, which could have several reasons due to the influence of many variables in the thrust calculation. First, it can be assumed that the operational thrust calculated from the given flex temperature is not correct, as it is based on generalized or empirical correction factors (eq. 3) that may be inaccurate for this particular engine model. Second, the lift-off point is only estimated geometrically, which may lead to an incorrect takeoff run length and acceleration at takeoff (eq. 2). Third, the BADA-based performance parameters for the Airbus A319 apply to a different engine model (IAE V2500) than the A319-112 (CFM56).

Validation of noise calculation

The results were separated by NADP1 and NADP2 to avoid falsification by averaging. In the following discussion, only the results for comparing the measured and calculated noise levels of the NADP1 flights are addressed. However, the results for NADP2 show the same trends. It should be noted, that radar data doesn't represent the true aircraft position (see Input data) and the measured noise levels may contain errors too.

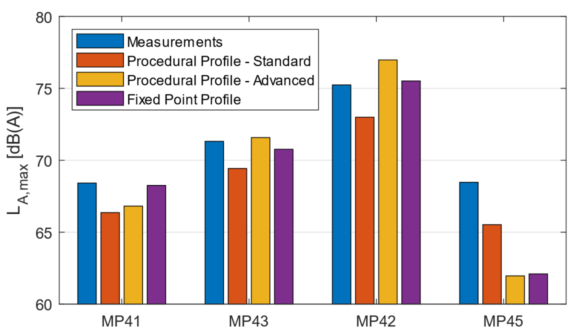

Fig. 4: Mean $L_{A,MAX}$ for all NADP1 flights

The mean $L_{A,MAX}$ (measured and calculated) of all flights is illustrated in Fig. 4. Along all MP (besides MP45, located north of the airport), the noise levels calculated with fixed point profiles are closest to the measured values. The big differences at MP45 are most likely due to low elevation angles between aircraft and receptor during takeoff run or initial climb as well as refraction, reflecting and shielding effects, which are not modelled yet [8].

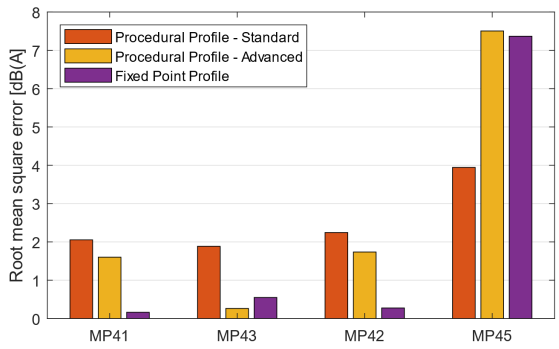

Fig. 5: Root mean square error (RSME) of all NADP1 flights

The RMSE for all variants and MP between measured and calculated noise levels is illustrated in Fig. 5. Besides MP45 and MP43, the RMSE for the fixed point profiles is clearly below the procedural variants and close to the measurements (max. RMSE at MP43 with 0.5 dB(A)). The high deviations of the procedural profiles can be explained by higher altitudes modelled along the flight path versus the fixed-point profiles, which, on the other hand, accurately represent the radar trajectory. In addition, we only provided T_{BRP1} and m_{BRP} at the BRP for the procedural profiles and the flight performance along the trajectory was then calculated with AEDT. Looking at Fig. 5 and based on the NPD-relationship underlying the noise calculation algorithm, it can be summarized that in addition to providing the actual aircraft mass and thrust (at least for the BRP), the correct flight altitude along the flight path is a key factor in minimizing differences between calculated and measured noise levels. In future research, we will compare the trajectories of the variants and analyze the geometry during the moment of closest point of approach between aircraft and receptor to identify the main drivers for differences between measured and calculated values.

Conclusion

In this paper, we have presented a methodology for estimating the performance parameters of departure flights, which form the basis for accurate individual aircraft noise calculations with AEDT. The methodology applies specifically to radar tracks where the takeoff run phase is not included. Although the availability of validation flights was limited, we showed promising results for the estimation of aircraft mass at the BRP. However, the thrust calculation depends on many influencing variables and is therefore less accurate. It is expected, that using ADS-B data (incl. the takeoff run segment) instead of FANOMOS-based radar data as core data input would lead to an improved performance estimation.

The implementation of fixed point profiles for noise calculation showed a very good match between measured and calculated noise values directly below the flight path and close to the airport, but not laterally to the flight path and in the vicinity of the airport. In future research work we will validate our methodology with flight data from certified full flight simulators (performance parameter estimation) and compare calculated noise levels of 170 departure flights with corresponding noise measurements.

Acknowledgements

Deutsche Flugsicherung (DFS OA/L) supported this research work by providing the radar tracks (FANOMOS format). Airport Berlin-Brandenburg (FBB) supported this work by providing noise measurement data for the validation flights.

References

[1] EASA, EEA, and EUROCONTROL, “European Aviation Environmental Report 2019,” Cologne, 2019.

[2] R. Guski et al., “WHO Environmental Noise Guidelines for the European Region: A Systematic Review on Environmental Noise and Annoyance,” *Int. J. Environ. Res. Public Health*, vol. 14, no. 12, p. 1539, Dec. 2017, doi: 10.3390/ijerph14121539.

[3] ECAC, *ECAC . CEAC Doc 29 4 th Edition Report on Standard Method of Computing Noise Contours around Civil Airports Volume 1 : Applications Guide*, 4th editio., Neuilly-sur-Seine: European Civil Aviation Conference, 2016.

[4] R. Caves et al., “Estimation of Civil Aircraft Performance and Operating Practices from Radar Data,” in *ICAS-98-6.11.1, 21st Congress of the International Council of the Aeronautical Sciences*, 1996.

[5] J. Sun et al., “Modeling and Inferring Aircraft Takeoff Mass from Runway ADS-B Data,” *7th Int. Conf. Res. Air Transp.*, no. 1, pp. 1–4, 2016.

[6] R. Alligier et al., “Learning the aircraft mass and thrust to improve the ground-based trajectory prediction of climbing flights,” *Transp. Res. Part C Emerg. Technol.*, vol. 36, pp. 45–60, 2013, doi: 10.1016/j.trc.2013.08.006.

[7] C. Struempfel, O. Lehmann, “Challenges and potentials of aircraft noise modeling using enhanced aircraft performance parameters and flight deck procedures,” in *Proceedings INTER-NOISE 2017,* 2017, pp. 3305–16.

[8] D. Rhodes, “Guidance on comparing calculated aircraft noise levels with measurements,”, CAA UK, 2018.

[9] M. Mitzkat, C. Strümpfel, “ Case Study on Aircraft Noise Reduction by Variation of Departure Profiles during Night Flights,” in *Deutscher Luft- und Raumfahrtkongress 2019*, 2020, doi: https://doi.org/10.25967/490198.

[10] B. Sillard, et al., “EUROCONTROL Experimental Centre: User Manual for the Base of Aircraft Data (BADA) Revision 3.13 - EEC Technical/Scientific Report No. 15/04/02-43,” Brétigny-sur-Orge, 2015.

[11] Airbus, “Getting to grips with aircraft performance - Flight Operations Support & Line Assistance. Concept Design SCM12, reference SCM-A226,” 2002.

[12] D. Poles, “EUROCONTROL Base Of Aircraft Data (BADA) Aircraft Performance Modelling Report - EEC Technical/Scientific Report No. 2009-009" Brétigny-sur-Orge, 2009.

[13] Federal Aviation Administration, “Aviation Environmental Design Tool (AEDT) 3b: Technical Manual,” Cambridge, MA, 2019.