ADS-B data usage for aircraft noise and air quality modelling and measurement during specific stages of LTO cycle

Kateryna Kazhan, Kateryna Synylo, Oleksandr Zaporozhets, Sergii Karpenko

ADS-B data usage for aircraft noise and air quality modelling and measurement during specific stages of LTO cycle

Kateryna Kazhan* and Kateryna Synylo

Department of Civil and Industrial Safety,
National Aviation University,
Kyiv, Ukraine
Email: kazhank@gmail.com
Email: synyka@gmail.com
*Corresponding author

Oleksandr Zaporozhets

Łukasiewicz Research Network – Institute of Aviation,
Warsaw, Poland
Email: Oleksandr.Zaporozhets@ilot.lukasiewicz.gov.pl

Sergii Karpenko

Research Department,
National Aviation University,
Kyiv, Ukraine
Email: karpenko_serg@ukr.net

Abstract: The paper is targeted at the analysis of the importance of Automatic Dependent Surveillance-Broadcast (ADS-B) data in the terms of overcoming gaps between aircraft noise and local air quality modelling results and their short or long-term measurements. Presented results based on noise and air pollution measurement campaign at Ukrainian airports describe general peculiarities of the pre-processing and usage of ADS-B data during specific stages of aircraft landing and taking-off (LTO) cycle in the airport. The outcomes could be used for more accurate noise and air pollution exposure assessment and the development of recommendations for noise and local air quality monitoring systems in airports under consideration.

Keywords: aircraft noise; air quality; airport; modelling; measurement.

Biographical notes: Kateryna Kazhan is an Associate Professor at the Department of Civil and Industrial Safety of the National Aviation University (NAU, Kyiv, Ukraine). In 2013, she defended PhD-thesis on Environmental Safety at the NAU. Her research interests include aviation noise modelling and measurements, noise and emission interdependencies, and mitigation of

aviation impact on local communities. She is involved in various industry consultancy projects, particularly in Environmental Impact Assessment and noise zoning.

Kateryna Synylo is an Associated Professor at the Department of Civil and Industrial Safety of the National Aviation University (NAU, Kyiv, Ukraine). In 2013, she defended PhD-thesis on Environmental Safety at the NAU. Her research interests include aviation emission and air pollution modelling and measurements in airports, noise and emission interdependencies, and mitigation of aviation emission impact on environment. She is involved in various industry consultancy projects, particularly in environmental impact assessment and environment protection programs in airports.

Oleksandr Zaporozhets is an Area Leader for Research – Professor at the Łukasiewicz Research Network-Institute of Aviation in Warsaw since 2022, a researcher and teacher at the National Aviation University (NAU, Kyiv, Ukraine) between 1978–2021. He has been involved in numerous international studies and projects related to environment protection from civil aviation impact, concentrating on the assessment of balanced approach options for the reduction of environmental problems. He is an official expert of Ukrainian CAA in environmental safety of the civil aviation. From the 2009 till 2020, he is a nominated member of ICAO CAEP from Ukraine.

Sergii Karpenko is a Research Associate of the Acoustic Laboratory at the Research Department of the National Aviation University (NAU, Kyiv, Ukraine). In 2021, he defended PhD-thesis on Environmental Safety at the NAU. His research interests include aviation and environmental noise modelling and measurements, and mitigation of noise impact on local communities. He is involved in various industry consultancy projects, particularly in environmental impact assessment and noise zoning.

This paper is a revised and expanded version of a paper entitled 'Peculiarities of pre-processing of ADS-B data for aircraft noise modeling and measurement during specific stages of LTO cycle' presented at International Symposium on Electric Aircraft and Autonomous Systems 2021, Eskisehir, Turkey, 16–18 December 2021.

1   Introduction

Assess aircraft noise levels and air pollution accurately is a constant problem of their exposure and impact management around the airports. Calculations and measurements are both important for this purpose. In accordance with the provisions of the Environment Noise Directive (END, Directive 2002/49/EC, 2002) and the ICAO Balanced Approach (ICAO Doc 9829, 2004), the task of noise zoning should be fulfilled on the basis of noise indexes – L_{den} and L_{dn}. Although Ukrainian Rules AR-381-2019 (SAAU AR-381, 2019) under the transposition of the END reference offer to use noise indicators L_{den} – for evaluation of aircraft noise impact on the population, the Rules (SAAU AR-381, 2019) do not contain normative noise limits for noise zones, so as they are absent in national Sanitary and Building Rules (SSR-173, 1996; DSTU-N B V.1.1-31, 2013). The impact on the population by noise is dependent on these criteria, first of all, especially the human annoyance (Zaporozhets and Blyukher, 2019). Their values should be calculated or

measured grounding on the assessment of sound exposure level *SEL* (L_{AE}) and/or maximum sound level L_{Amax} for the specific events, which are contributing to the value of noise index [or to the equivalent L_{Aeq} sound levels, which are still used for limiting the acoustic norms in Ukraine by the Rules (SSR-173, 1996; DSTU-N B V.1.1-31, 2013)].

Instrumental measurements of aircraft noise are performed in accordance with the requirements of International Standard (ISO 1996-1, 2016) and the guidelines (SAAU Order 585, 2020) to the Rules (SAAU AR-381, 2019), which are intended for use in determining the characteristics of aircraft noise in existing housing and residential areas planned for new construction in order to further establish compliance with the requirements of sanitary and construction norms and other state standards. Separate aircraft flight noise events are assessed usually by sound exposure *SEL* and maximum sound levels L_{Amax}. According to ISO 20906 (ISO/CD 20906, 2009) for successful processing of monitoring data, in addition to long-term measurements, the selection of the sound event associated with the aircraft involved in the event is necessary, as well as its classification and identification. For their calculation at a point of noise control or for the noise contour definition (aircraft noise footprint for specific aircraft type and type of the noise criterium) the ICAO Doc 9911 (2018) and ECAC Doc 29 (2016) are used in similar way as for cumulative values of the noise indexes, but both documents declare that their accuracy for noise event's level calculation is much less than for cumulative noise index or equivalent level. Measuring aircraft noise and noise monitoring in the vicinity of an airport to achieve the main goal – reducing the population affected by noise and improving the quality of life – requires a relevant organisation of field acoustic research. But as a practical experience shows (Zaporozhets et al., 2021; Abhyankar et al., 2019) the difference between measured and calculated noise events' levels is usually observed, both for aircraft departures and arrivals, and it may be quite big. In such a case, the requirement of the guidelines (SAAU Order 585, 2020) for confirmation of calculated results with measurements may confuse any authority involved in process of noise zoning around the airports. The proper explanation of differences between measured and calculated noise events' levels is necessary, so as a reduction of these differences, especially if they are higher than the accuracy of the aircraft noise calculation method.

Table 1 Area of noise restricted zone at different airports on the basis of criteria: $L_{AmaxN} = 70$ dBA and $L_{AeqN} = 50$ dBA

Airport	$L_{AmaxN} = 70$ *dBA, km²*	$L_{AeqN} = 50$ *dBA, km²*
Boryspil' (UKBB)	326.1	94.1
Dnipro (UKDD)	59.3	14.8
Antonov-2 (UKKM)	450.4	37.8
Mylolaiv (UKON)	120.1	11.1
Odesa (UKOO)	71.2	15.1
L'viv (UKLL)	*63.3*	11.9

The criterion L_{den} belongs to the group of the equivalent sound levels that could be applied for zoning purposes, however there are some countries in European region where maximum noise level defined as the legislative limits to protect environment and first of all population from noise (for example, Ukraine has both types of limits (SSR-173, 1996; DSTU-N B V.1.1-31, 2013; SAAU AR-381, 2019; Konovalova and Zaporozhets, 2021) – equivalent (L_{Aeq}) and maximum (L_{Amax}) sound levels). In the current circumstances of air

traffic in Ukraine the noise contours L_{Amax} occupy a 3–5 times larger area than noise contours L_{Aeq} (Table 1), and thus, defines boundaries of noise restricted zones. The form and size of noise protection zones (defined on the maximum sound level L_{Amax}) are very sensitive to real track dispersion relatively nominal track, flight altitude, and total assessment of the operation scenarios (Figure 1).

Figure 1   Two approaches to noise zoning on the basis of L_{Amax} (see online version for colours)
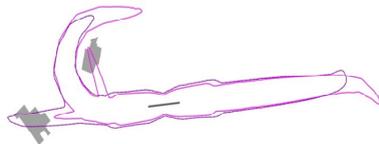
Note: Purple – AIP as a sources of track information; magenta – averaged ADS-B tracks
        and flight data: grey – residential areas.

To clarify the results of aviation noise modelling at the airport under consideration and to explain the possible differences (due to gaps in input data, particularly defined by supervised flight trajectories in operation) between measured and modelled results, open track data based on the results of Automatic Dependent Surveillance-Broadcast (ADS-B) surveillance were analysed (in particular, the results are presented on the FlightRadar24 and OpenSky websites). According to ADS-B surveillance technology, aircraft determines its position using satellite, inertial and radio navigation systems and transmits it (approximately 1 sample per 1 second) periodically with other relevant parameters to ground stations and other equipped aircraft. The signals are transmitted at a frequency of 1090 MHz. The receiver's ADS-B antenna is capable of receiving messages from aircraft up to 400 km away. However, for aircraft at lower altitudes, the range may be significantly limited. Especially for aircraft that are on the ground, or in the stages immediately before landing or in the initial stages of take-off (Schultz et al., 2020). Current studies only analyse the airside and ground trajectory stages with open sources for aircraft movement data, which may be only the part of new concept of flight data incorporation in AN and LAQ assessment in/around airports. Further research expects for incorporation of the aircraft movement data necessary for correct real flight profiles presentation and their usage for the same AN and LAQ calculations in vicinity of the airports.

The possibility of using pre-processed FlightRadar24 data, in particular for the purpose of modelling aviation noise and air pollution generated at different stages of aircraft landing and taking-off (LTO) cycle, was analysed for test case at different airports in Ukraine: ground stage (UKBB, UKKK); departure (UKKM) and arrival (UKKM, UKKK). Analysis was done for the main purpose to calculate noise levels correctly, as for local air quality assessments, which are the same necessary for environmental protection management in airports.

2   Analysis of track data in terms of noise event reconstruction

The importance of taxiing noise modelling, as indicated in many studies (National Academies of Sciences, Engineering, and Medicine, 2009, 2013; Zaporozhets et al., 2021), is not always the same. On the surface, aircraft engines spend most of the time at

or near idle, the operating point at which the engine is least efficient and where the greatest concentrations of certain species of pollutants are produced (Sweriduk et al., 2011). Of course, the aircraft operation on ground is highly important for local air quality assessment (Synylo et al., 2021). For some of the airports because of the specific aerodrome layout, infrastructure, and much quieter aircraft in operation due to the ICAO Balanced Approach (ICAO Doc 9829, 2004) influence on acoustic performances of new aircraft designs the aircraft taxiing in any airport may contribute essentially on noise footprints (Zaporozhets et al., 2021). The usage of aircraft real trajectories along the apron and taxiways before take-off and after landing, engine mounting height and engine operating mode should be taken into account during noise modelling and measuring for such airports, as Kyiv/Zhulyany (UKKK), Kharkiv (UKHH), Zaporizhzhia (UKDE), located nearby residential areas, or inside the city directly and on closer distances from the apron and taxiways to multi-storey buildings that from the runway (UKKK).

The ADS-B data processing technology includes few steps that have to be performed in order to extract ground tracks (in horizontal plane) and the paths (in vertical plane) for aircraft flights. Paths tracked by individual ADS-B receivers or generated by aggregators (FR24), receiving information from many receivers at the same time, require pre-processing of data to avoid the false data. The study of such erroneous data can be useful in terms of improving the monitoring system or correcting the location of receivers.

2.1 Taxiing

The airport (aerodrome) layout can set the priority at some area (points) of noise assessment from aircraft on taxiway compared to aircraft in flight, including noise from aircraft on the runway, i.e., during their take-off and landing. In Figure 2 (Report G 10.1, 2006), it can be seen that at Frankfurt airport noise from the ground LTO stages significantly increases the noise contours for sound levels of regulatory values, so the removal of ground stages from the calculation (or measurement) of sound levels is an inappropriate in this case. The overall result is that ground operations can make a greater contribution to airport noise pollution, so there is a need to include them in future airport noise assessments, which are needed in airport design studies, master plans, environmental assessments and impact reporting on the environment.

A similar situation is observed at some airports of Ukraine. For example, at the Kyiv/Zhulyany airport (Figure 3) the apron with aircraft stands near the terminals is located at a distance of more than 1 km from the runway axis and the contribution of noise from of aircraft taxiing and maintenance to the total noise load on residential areas in Kyiv, especially in the North of the airport (on Povitroflotskaya Street, the nearest building to the aircraft stand on the apron is 400 m away, to the runway – 1,500 m). In such and similar cases, projects to assess the sound levels of airport noise should include contribution from the ground stages of the aircraft movement – taxiing and operation/maintenance on stands [in Figure 3(a) passenger aircraft stands are close to passenger terminal, business aviation stands and aircraft engine run-ups at MRO]. Noise contour for L_{Aeq} = 65 dBA in 1990s traffic scenario [Figure 3(c)] was ~10 times larger then the same in 2010–2020 decade [Figure 3(b)] and covered the area with aircraft stands and taxi ways, so it was not necessary to assess the contribution from these noise sources previously.

Figure 2   Comparison of noise contours from ground and flight operations (Report G 10.1 2006) (see online version for colours)
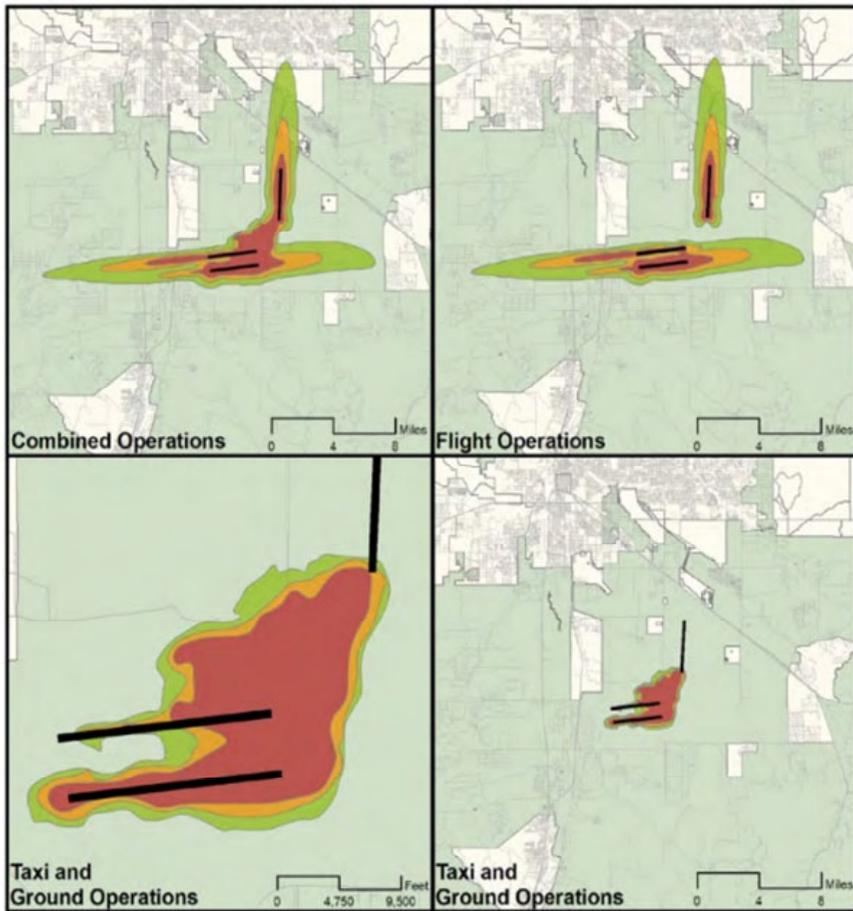

Notes: green – 55 L_{dn}; orange – 60 L_{dn}; red – 65 L_{dn}

That is, the modern integrated model of aircraft noise estimation must estimate not only contributions from aircraft flight trajectories (as interpreted by manuals including the ICAO Doc 9911 (2018) and ECAC Doc 29 (2016), but also from ground tracks of aircraft movement and operation in stands conditions [or aircraft engines' operation, for example during engines run-ups after their repair at the MRO plant – 'MRO' in Figure 3(a)].

Taxi time is a major contributor to airport performance. According to the airport layout, it is expected that different average taxi distances, times and deviations exist. ADS-B data processing for aircraft ground operation is provided for ground tracks only. It is the easiest to process from ADS-B data, transmitted in the form of individual messages MSG 2, which may be easy to separate from the general flow of flight data. At the preliminary stage it is necessary to exclude trajectories from the general stream with following data (Schultz et al., 2020): messages formed in the absence of GPS data; insufficient number of signals, which leads to missed points and false trajectories, which

is most evident in the ground stages due to mismatch with the geometric dimensions of the runway, taxiways and platforms (Figure 4).

Figure 3 Airport Kyiv/Zhulyany, (a) the apron with aircraft stands near the terminal is located at a distance of more than 1 km from the runway axis (b) noise zones for 2010–2020 air traffic scenario – red contour is for L_{eq} =65 dBA (c) comparison of noise contours for 2010 and 1990 air traffic scenarios – noise area for L_{eq} =65 dBA reduced from $2.5911 \cdot 10^7$ m² in 1990s till $3.7231 \cdot 10^6$ m² in 2010s (see online version for colours)
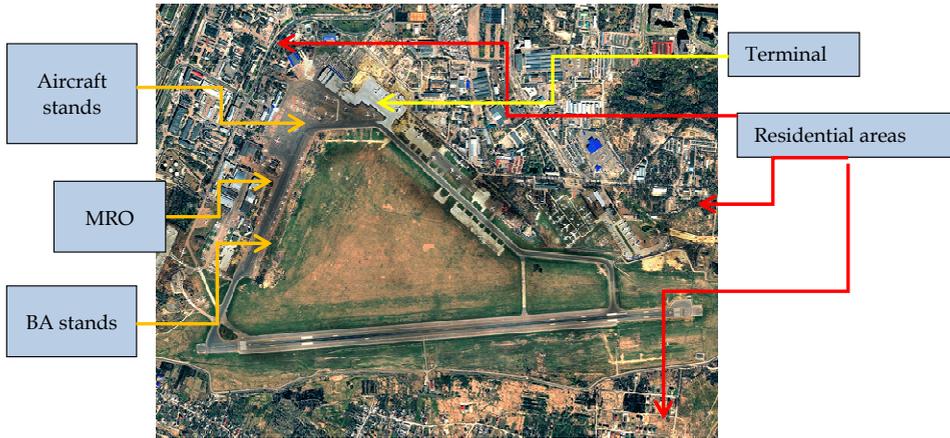
(a)

(b)
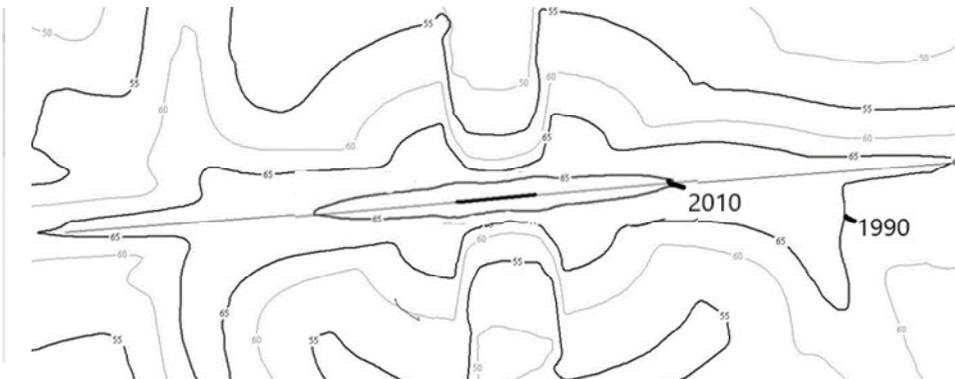
(c)

Such changes in tracks based on the ADS-B data are usually connected (National Academies of Sciences, Engineering, and Medicine, 2009) with a lack of reception in the signal, for example breaks in the continuous transmission of a signal due to radio interruptions. The location of the receivers is the other important factor. Aprons often are not in the zone or the reception. For example, according to the FR24 data for the UKKK aerodrome, there are a number of receivers operated in a stable mode (more than 97% of total working time). However mutual influence of factors such as the location of the receiver, relief features and large distance from the runway to aprons (over 1 km) leads to the low data quality during taxiing (Figure 4).

Three possible locations of receivers were analysed in the current research (Figure 5). The best efficiency in terms of assessment of environmental factors (noise, air pollution) for ground stages of aircraft movement was defined at the airfield or very close to the outer perimeter of the aerodrome [Figure 5(a) – for example, point A2]. The main recommendation for selection of final location of the receiver for tracking of ground operation is providing line of sight with moving aircraft from the moment of start of runway operation to final location at apron.

Figure 4   Examples of distortion of the aircraft trajectory during ground operation, (a) aircraft taxiing from the runway (b) movement on the apron; UKKK, October –November 2021 (see online version for colours)

(a)   (b)

Figure 5   Location of additional receivers A1-A3 (a) and track (yellow) correspondence to runway and taxiways geometry (A2) (b) (see online version for colours)

(a)   (b)

Of course, the correct definition of ground tracks for aircraft taxiing is a necessary requirement for accurate air pollution calculation from aircraft engine emission also (not only for correct calculation of noise load from the airport activities), which is dominant for airport scenario of LAQ assessment. In the general case, the aircraft compute their position within uncertainty margins (navigation accuracy) according to actual sensor sources (such as global navigation satellite system, inertial navigation system, or radio navigation) and broadcast their position via ADS-B. The uncertainty analysis is out of the scope of this paper and chose to manually filter irrelevant data as part of the pre-processing step written before. The final results shown in Figure 4 and Figure 5 completely satisfy the requirements of accurate aircraft noise and LAQ calculations from ground airport activities.

2.2 Arrival tracks

Measured arrival altitudes tend to be close to the modelled altitudes at the shorter track distances, higher than the modelled altitudes at the middle distances, and lower than modelled at the furthest track distances (National Academies of Sciences, Engineering, and Medicine, 2009; Zaporozhets et al., 2011). There is shown in Figure 6 for research made in Kyiv airports currently, mainly with Antonov aircraft. The results of the comparison of the calculated values at the measurement points with the measured sound levels for PS AN148 are shown in the Table 2. The relative position of the microphones at the measuring points (TB1-TB3) on the vertical profiles of descent before landing and take-off is shown in Figure 6.

For the descent and approach stages, the ground track dispersion is significantly lower: the deviation does not exceed 200 m at a distance of 6 km (Figure 7) for the same flight (October-November 2021). Very different picture can be observed for manufacturing airport UKMM: test flight data compared with AIP recommendation are significantly different. Such differences, taking into account very rare flight events, lead to the significant gap in modelled and measured results only because of dispersion of ground track trajectories. Additionally, the altitude dispersion should be included into noise calculations.

Table 2   The results of comparison of the calculated with the measured sound levels at the measurement points for the aircraft An-148, dBA

Point no	Arrival				Departure			
	Calculated results		Measured results		Calculated results		Measured results	
	L_{Amax}	SEL	L_{Amax}	SEL	L_{Amax}	SEL	L_{Amax}	SEL
TB 1	99.3	98.8	98.4	98.8	89.6	95.4	91.6	95.8
TB 2	90.1	93.7	86.9	93.4	82.3	89.9	-	-
TB 3	78.8	85.7	-	-	70.6	82.1	67.4	67.3

Figure 6   Comparison of (a) landing (take-off) and take-off (b) profiles of An-148 and An-124 aircraft, and location of measuring points (TV1, TV2, TV3), x-axis – distance to KTA, m; y-axis – the height of the aircraft above sea level, m (see online version for colours)
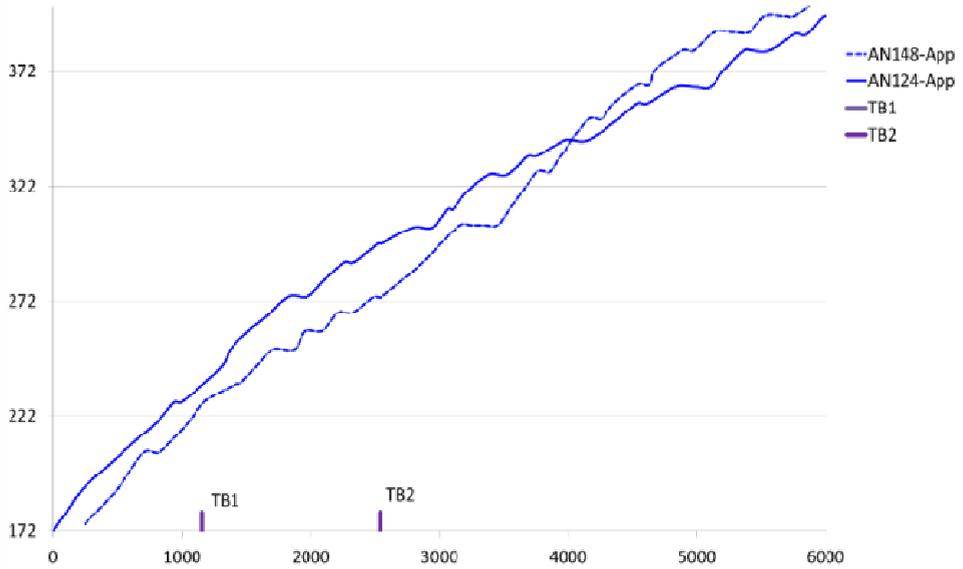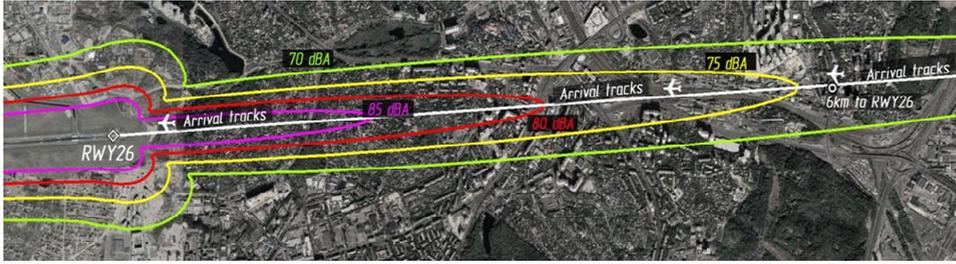

(a)
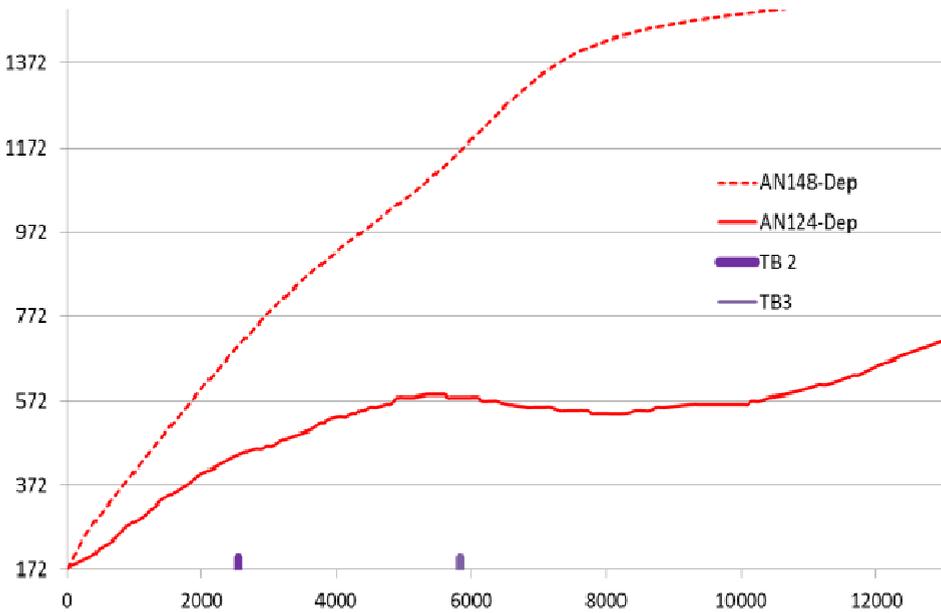
(b)

Figure 7   Track dispersion (white lines) during descent and arrival procedures, typical for city airport; 70-85 dBA are L_{Amax} noise levels (see online version for colours)


2.3   Departure tracks

Vertical take-off/climbing profiles of the aircraft An-124, An-148 is presented in Figure 8. Comparison with take-off profiles using modern models of AN propagation (in particular, INM) (for aircraft types analogous to An-124, An-148 according to the recommendations of Recommended ANP Aircraft Substitutions (https://www.aircraftnoisemodel.org/aircraft/substitutions) showed that the differences in the results of modelling the levels of AN at points close to the aerodrome. Figure 9 shows the comparison of simulation results during the operation of the aircraft on the nominal route (Bo2T), taking into account only the trajectory of the route fixed by ADS-B (TrackAN148) and taking into account the flight altitude above the design points (Track.H.V-AN148). With the distance from the runway the results of modelling on nominal routes differ significantly from the actual trajectories of the aircraft.

Figure 8   Comparison of take-off profiles, (a) An-148 and (b) An-124 used in INM and actual take-off profiles based on ADS-B results (see online version for colours)
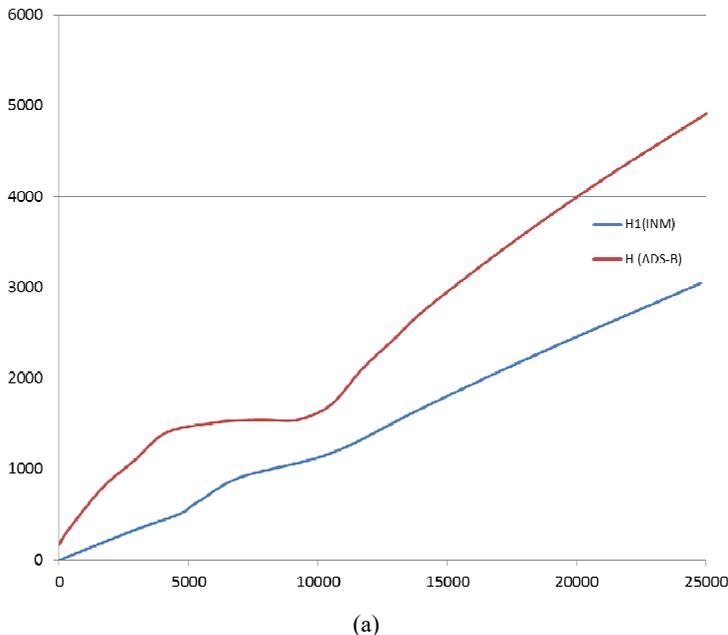

(a)

Figure 8   Comparison of take-off profiles, (a) An-148 and (b) An-124 used in INM and actual
take-off profiles based on ADS-B results (continued) (see online version for colours)
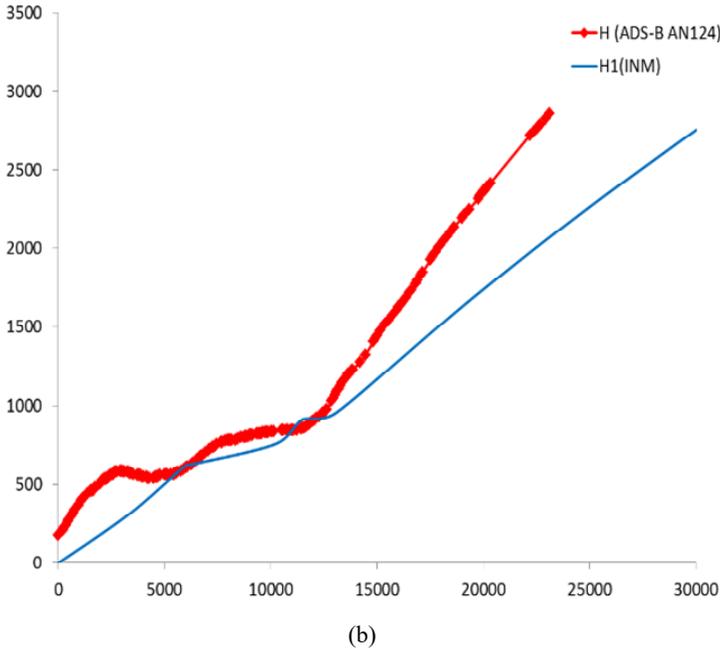
(b)

Figure 9   Levels of AS L_{Amax} at calculation points D1-D13 according to the results of modelling
during operation of aircraft type, (a) AN148 and (b) AN124 during take-off and
ascent on nominal routes Bo2T / BRP2T, taking into account only the trajectory of
the route obtained using ADS data-B (Track) and taking into account the flight height
above the calculation points (Track.H.V-AN148) (see online version for colours)
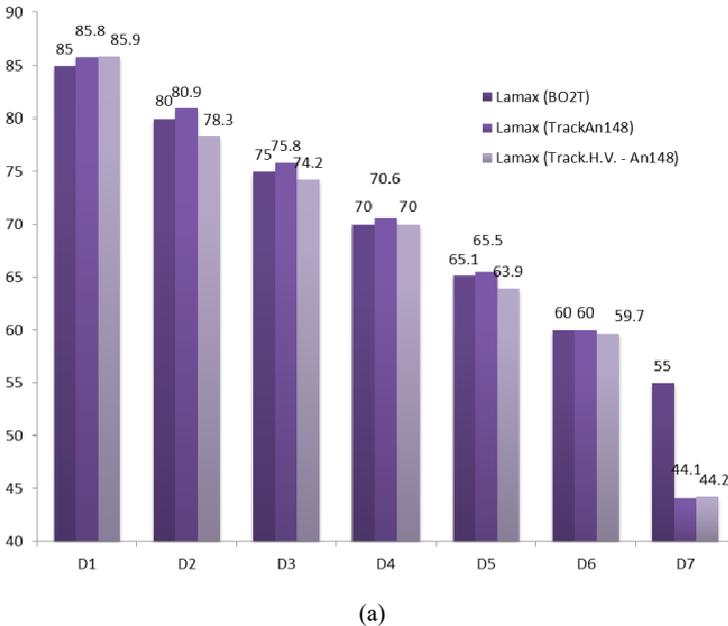
(a)

Figure 9 Levels of AS L_{Amax} at calculation points D1-D13 according to the results of modelling during operation of aircraft type, (a) AN148 and (b) AN124 during take-off and ascent on nominal routes Bo2T / BRP2T, taking into account only the trajectory of the route obtained using ADS data-B (Track) and taking into account the flight height above the calculation points (Track.H.V-AN148) (continued) (see online version for colours)
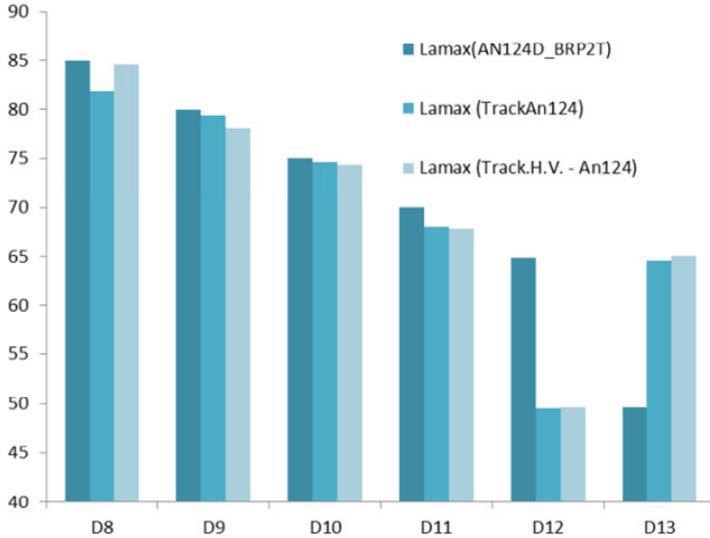
(b)

The horizontal dispersion of take-off tracks for the same flight performed on A320 aircraft during October 2021 for runway end 26 is shown in Figure 10. As shown, such a dispersion of tracks can affect the acoustic situation in the vicinity of the aerodrome, changing the shape of the contours of equal noise, determining the boundaries of the noise restricted zones for the residential development. Thus, an important task for the take-off phase is to take into account the actual flight trajectories when modelling noise contours and substantiating the boundaries of residential restriction zones, as well as comparing the L_{Amax} sound levels obtained as a result of modelling and measurements.

Figure 10 Dispersion of take-off tracks for the same flight and its impact on the form of noise contours L_{Amax} = 70…85 dBA; A320, October 2021 (see online version for colours)

3   Local air quality studies

Local air quality nearby the airports is of the same importance as aircraft noise because of the impact on public health due to pollution over the standard limits of the character contaminants, the most important among them are the nitrogen oxides and particulate matter. Emission inventory assessment usually shows for airports that aircraft contribute dominantly (over 50% of total emission for the character contaminants) to air pollution in most possible operational scenarios.

Aircraft engine emission nearby airport is produced during LTO cycle, which is dominantly consists of the on-ground operation (engine run-up at stands, taxiing before departure and after arrival, running along runway during taking-off and landing, etc). The aircraft is quite a specific source of emission and air pollution due to a number of reasons:

1   During the LTO cycle the aircraft is a moving pollution source most of its duration, with dominance of on-ground operation (taxiing, engine running at stands and possible stops for waiting a decision for the next movement, etc) – close to ground surface and with highly varied emission factor during on-ground aircraft operation.

2   Engine exhaust gases jet transports the emitted contaminants on rather large due to significant momentum and thermal buoyancy of the jet flow. These distances are dependent from engine power setting first of all, but the direction of the engine exhaust, meteorological (wind direction) and engine installation (under the wing or tail installation) parameters, stage/mode of aircraft movement are also important.

3   Despite the ICAO (CAEP) specification of engine emission certification procedure – for specific thrust settings and their duration in LTO cycle, the real aircraft operational procedures in airport under consideration are not well adapted to these engine operation (thrust) settings, which are quite different from specified standard values. For example, ICAO thrust setting is defined strictly for 7% of maximum thrust, which usually very different from operational values between 2%–20% of maximum thrust for engine types in operation currently with highly varied emission factor inside this diapason. The same condition is character for flight engine modes during the climbing (defined by ICAO cycle 85% maybe different from real value for specific engine type) and descending (30% of maximum thrust in ICAO cycle is usually very different from real value between 20%–60% of the thrust).

Location of the aircraft – the coordinates and direction of the movement – is extremely important for accurate air pollution assessment inside and nearby the airport. The emissions contribution from runways (higher operational engine modes produce the maximum rate of NOx emission) and taxiways/engine run-ups (lesser operational engine modes produce the maximum rate of CO, HC and PM emission) to LAQ in airport can be different depending on the layout of the aerodrome and nearby residential areas. These differences were investigated in Zhulyany and Boryspil airports of the Kyiv with analysis of ADS-B data for aircraft movement (Figure 11). Both studies were performed to measure the concentrations of NOx, CO and CO_2 in aircraft engine jet and plume modes under observed operational conditions with main goal to provide real input data (emission index and maximum concentration) to be used for validation of emission factors and LAQ at the airports with complex model PolEmiCa.

3.1   Measurement campaign at Kyiv/Zhulyany Airport

Measurements were carried out at measurement site, which is located close to the main taxiway (~10 m) with a measuring height of 1.5 m. Argued location of monitoring station allow to catch the instantaneous maximum concentration in plume from aircraft engine at the stages of taxing, clearing of take-off, acceleration on the runway and further take-off, Figure 11(a).

Figure 11   Location of the air pollution monitoring station on the aerodrome, both downwind, (a) Zhulyany airport - stationary station is used alone (b) Borispil airport – stationary station A and mobile Station B (Van) are used together (see online version for colours)


(a)
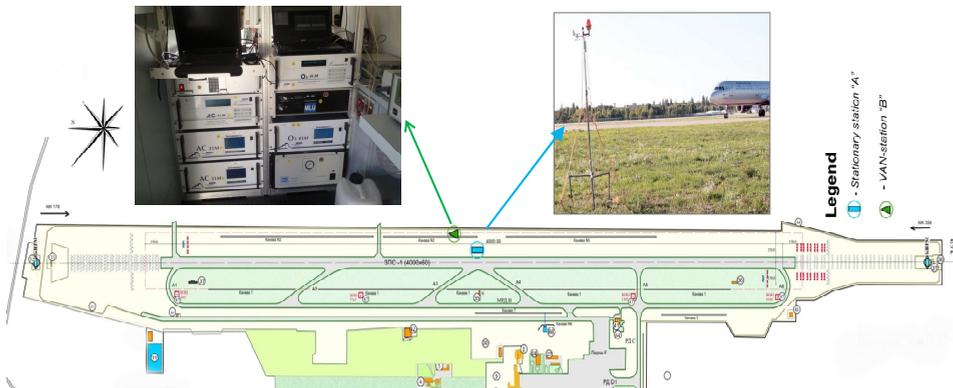
(b)

Analysis of measured instantaneous concentrations of the contaminants NO, NOx, CO demonstrates the following correlation (Figure 12):

- Taxiing of aircraft along the main taxiway causes the high concentration of NO, which can be explained by quite short distance to aircraft (~10 m) and the most part of total NOx is represented by NO in exhaust plume from the engine (short time for transformation to NO_2 in a plume).

- Stage of cleared for take-off before aircraft run is characterised by extremely high concentration of CO.

- Aircraft acceleration during take-off along the runway describes the detection at the point of monitoring of high concentrations of the nitrogen oxides NOx.

Figure 12 shows the background and aircraft plume concentration for NO, NOx and CO at 1.5 m sampling height for different aircraft at take-off (T/O) and ground taxi (TX) conditions, and it maybe seen a good correlation between the maximums for NO_2 and CO – especially for the stage aircraft clearing for take-off before its run. For both contaminants their instantaneous (temporal sampling per second) concentrations are over twice bigger the background levels, detecting the evident contribution of the aircraft emission plume in any sampling in accordance with their emission factor correspondent to the LTO mode.

Figure 12   Instantaneous concentrations for NO_2, CO at monitoring station under aircraft taxi and take-off conditions [location is shown in Figure 11(a)] – the background and plumes are evidently detected (see online version for colours)
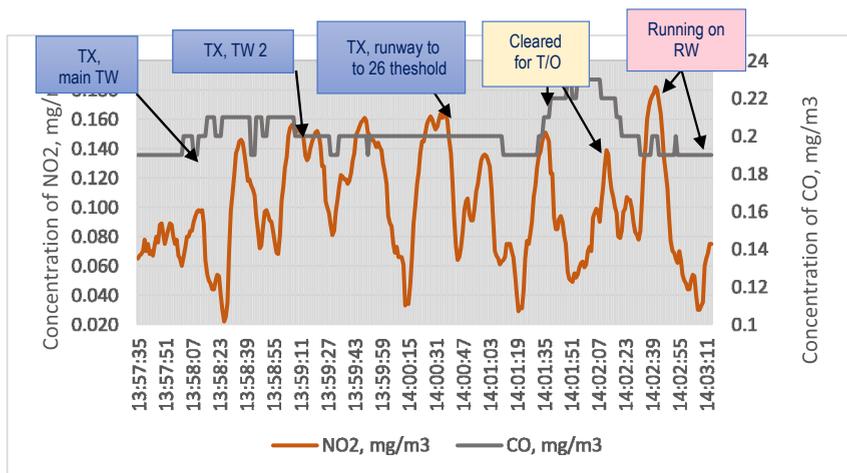

3.2   Measurement campaign at International Airport Boryspil

Experimental studies at International Airport Boryspil (IAB) were focused on measurement of NO_x concentrations in the plumes, both for plumes produced by the engine jet and by dispersion of pollutant in the air under real operating (taxiing and running along the runway during taking-off and landing) and meteorological conditions (Synylo and Kazhan, 2014; Synylo et al., 2016). Measurements were carried out at two sites, one was organised as a stationary station A (to supervise a jet-regime of the plume usually) close-by the runway (~30 m) with a sampling height of 3.0 m. A mobile station B (to supervise dispersion-regime) at varying distances and locations from the

runway due to prevailing wind direction and with a sampling height 3.6 and 5.7 m (Figure 13). This measurement layout may guarantee that the aircraft engine exhaust should be scanned by NO_x sampling devices. CO_2 samples are convenient to detect the plumes – the occurrence of engine exhausts transportation (aircraft emission and pollution events similar to aircraft noise events in temporal domain) at the point of monitoring over the background concentrations. The data in Figure 13 exhibited that concentration peaks for NO_x and CO_2 events are definitely correlated between themselves and with aircraft plumes.

Figure 13 Instantaneous concentrations for NO, NO_x and CO_2 at mobile monitoring station B in IAB [location is shown in Figure 11(b)] – the background and plumes are evidently detected (see online version for colours)
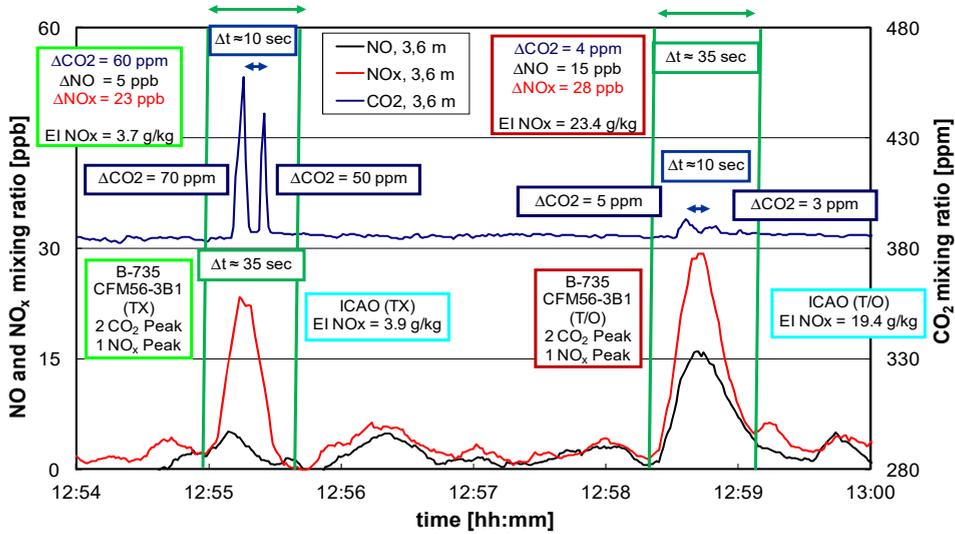

Figures 12 and 13 for both studies (UKBB, UKKK) show the quasi-stable background and quickly changing plume concentrations for NO, NOx and CO_2 at sampling heights for different aircraft types at different LTO stages (take-off – T/O and ground taxi – TX). Taking-off operation mode provides the highest NO_x emission, while the taxi mode – the NO_x emission and concentration are much lower. Because of close distance from the aircraft the Figure 13 detects a quite clear separated occurrence of exhausts from both engines of the same aircraft with delay time between these two events ≥ 10 sec (peak by peak). Also TX and T/O events at jet-regime of the plume are evidently detectable for Boeing B735 with two CFM56-3B1 engines.

The separate exhausts for each engine of the aircraft may be assessed as separately dispersed plumes at the monitoring station because the time of their transfer to the monitor is quite different for each engine. The maximum instantaneous concentration c_{max} at the monitoring station is derived at the moment t_{max}, which is determined from the transport distance of the pollutants x_{wind} and wind velocity u_w [Figure 14(a)]. For example, in UKBB studies for big aircraft the difference between t_{max} for the two separate exhausts was assessed at ~60 s due to the small angle between the wind and rolling directions. Depending on the resolution time of the equipment it may be possible to detect the total plume of the exhaust inside the interval of the averaging [red (1) and

blue (2) lines for the results with and without engine jet involved in calculation in Figure 14(b)] – this condition may provide a maximum concentration for this case; or to detect half of the plume inside the interval of the averaging – for this case it will be a minimum value of the concentration for this interval [light blue (3) with engine jet and green (4) without engine jet in Figure 14(b)]. For each aircraft take-off, the speed and direction of the wind were measured by an ultrasonic anemometer with a time resolution of 30 s providing the possibility to calculate the turbulent diffusion coefficients (K_X, K_Y, K_Z) appropriate to measured values of the concentrations and to use them for more accurate calculations (Zaporozhets and Synylo, 2016).

Figure 14 Calculation details for air pollution assessment from the aircraft engine exhausts, (a) calculation scheme for the transport and dilution of the pollutants in the exhaust gas jet from an aircraft engine and atmospheric diffusion (b) instantaneous concentration in engine plumes during 60 s (see online version for colours)

(a)

(b)
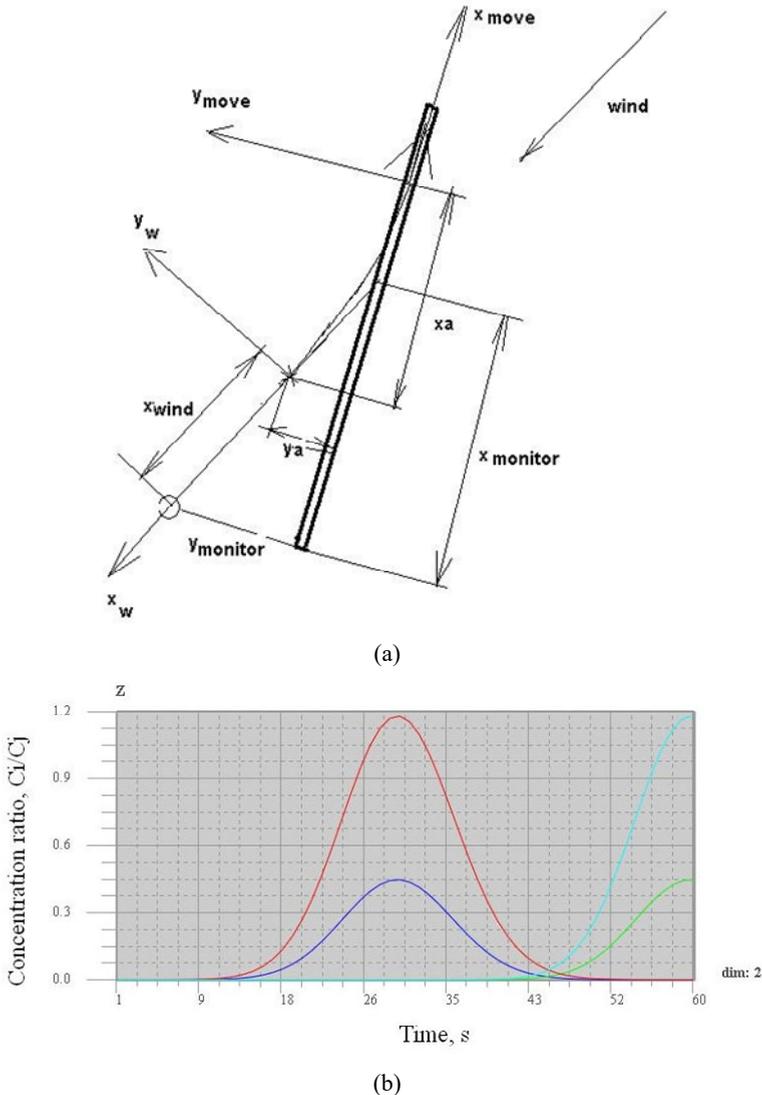
Possible reasons for the observed differences and their reduction between modelled and measured concentrations are as follows:

- The averaging period for the measured concentration (1 min) is quite long for the detection of the separate maximum concentrations in the plumes from every separate engine of the aircraft and to include their contribution to the measurement data. ADS-B data provides more correct aircraft coordinates and correspondence with time resolution for concentration assessment, especially by including in the calculation of the preliminary (before transfer by wind) pollution transfer by jets from the separate engines – the difference between the calculated and measured c_{max} may be reduced on ~20% (Synylo et al., 2015).

- Emission factors – the values of aircraft engine emission indices – are used usually for modelling purposes from the ICAO certification databank, which are normalised to average meteorological and airport layout conditions. Only the difference equal to 10°C in ambient temperature may comprise 10% of the accuracy due to the effect on the input and output data of the model. ADS-B data may provide the real aerodrome layout parameters, which must bring closer the calculated indices and concentrations to the measured ones.

- ADS-B data are necessary for accurate calculation of the distances between aircraft and monitoring station, which may accurately differentiate the pollution transfer by engine jet and by wind – small accuracy difference in coordinates assessment equal to 10% may provide ~100 m inaccuracy for instantaneous aircraft location and accordingly – zero concentration at monitor site.

### 3.3 Emission indexes under operational conditions

The obtained results of the studies within Kyiv/Zhulyany and Kyiv/Boryspil Airports confirm the possibility and necessity of organising continuous instrumental monitoring to assess the concentrations in the air as a result of emissions of aircraft engines within the airport. On the basis of the measured NOx, CO_2 concentrations in the jet-plumes from aircraft engines, the indexes EINOx were calculated corresponding with operational conditions and compared with ICAO databank values. The both values of the emission indexes were used for calculation the concentrations with PolEmiCa modelling tool. The difference between the measured and modelled NOx concentrations are significantly smaller for the determined indexes EINOX under real operational conditions, confirming the influence of operation conditions and their dominance over the standard ICAO conditions used for engine emission assessment, Figure 15. The calculated concentrations by modelling tool PolEmiCa include the contribution of engine jet buoyancy height, horizontal and vertical deviation produced by ground and wing trailing vortices, etc.

The results of the measured concentrations in the plumes from aircraft engines at both airports (UKBB, UKKK) were used for the improvement and validation of the complex model PolEmiCa. ADS-B data detected strictly the aircraft location (instantaneous coordinates and speed), jet plume analysis – engine operation mode with further higher accuracy of emission factor, engine jet buoyancy height and length over the ground surface. This contribution from the measurement system improvement with ADS-B involvement provides 10%–20% less difference between measured and calculated concentrations, so the accuracy of the modelling improved substantially.

Figure 15   Comparison of the measured and calculated NOx concentrations at station B in IAB studies, (a) height of monitoring 3.6 m (b) height of monitoring 5.7 m (see online version for colours)
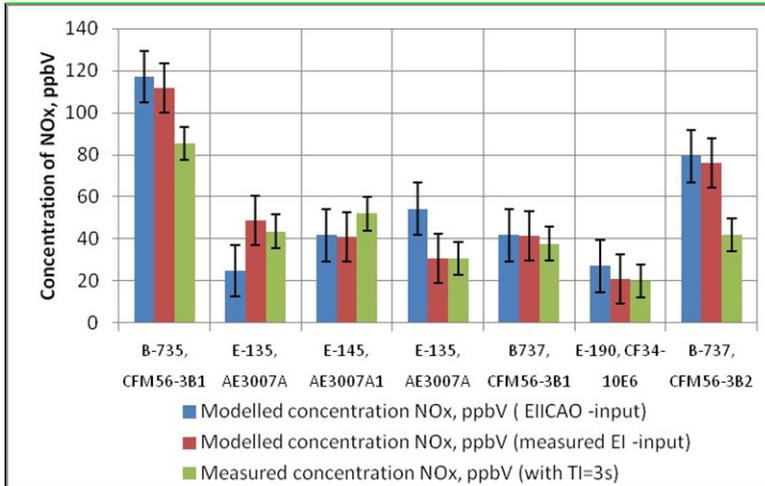
(a)
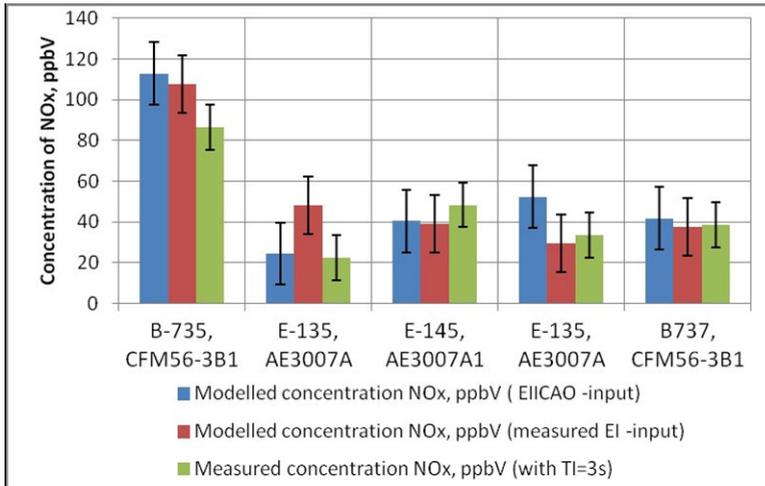
(b)

4   Results and discussion

Monitoring of aircraft AN and LAQ surrounding an airport is important to ensure the safety/security as well as quality of life for nearby of population - the residents living at nearby areas. The traditional method of tracking aircraft position, necessary for identification of the source of AN and air pollution, involves the ubiquitous rotating active radar, and the traditional method of monitoring aircraft noise is the single omni directional microphone and/or air pollution is the single sensor for any of the polluting species under consideration. Both of these systems still have significant disadvantages. In

the past several decades, microphone array acoustic monitoring systems have become widely known although they are typically practical only for research purposes.

The complex measurements of aircraft noise and air pollution in addition to ADS-B data recording were performed in the vicinity of airports (UKMM, UKKK, UKBB). The results have shown that calculated altitude of flight is higher that standard modelled altitude at noise tool (INM, AEDT) because of shifted moment of runway touching in comparison with AIP data about displaced thresholds. This causes the changes in NDP-dependencies. The results of the altitude and thrust correction are presented in Table 3.

**Table 3**   Comparison of measured and modelled data on example of Airbus-321

POINT	Modelled data	Measured data	Difference	Correction	Difference (corrected)
L_{Amax}, dBA					
MP2	89.4	95.2	−5.8	91.8	−3.4
MP3	84.2	88.01	−3.81	85.6	−2.41
SEL, dBA					
MP2	94.4	96.7	−2.3	95.1	−1.6
MP3	91.1	90.91	0.19	90.9	−0.01

Figure 16   Comparison of measured and modelled noise levels, (a) and concentrations (b) of the pollutants (see online version for colours)
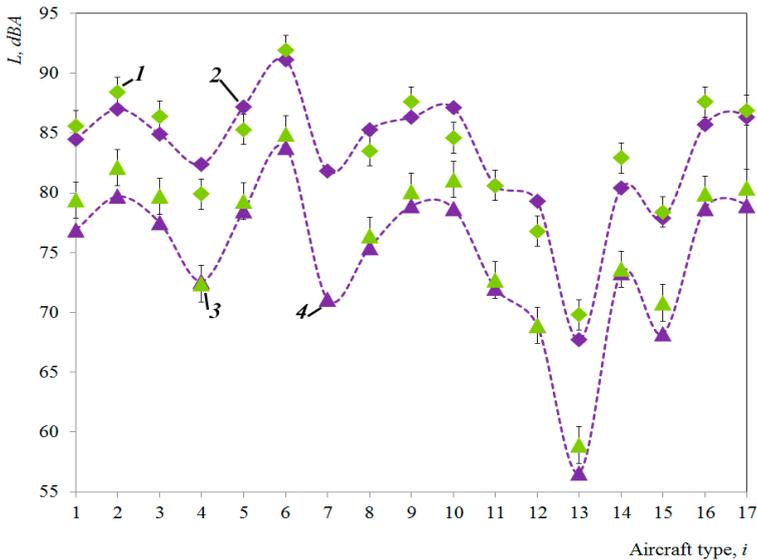
(a)

Notes: 1 – calculated *SEL*, dBA; 2 – measured *SEL*, dBA; 3 – calculated L_{Amax}, dBA; 4 – measured L_{Amax}, dBA; 5 – calculated NOx concentration during taxiing C(NOx), µg/m³; 6 – measured NOx concentration during taxiing, µg/m³; 7 – calculated NOx concentration during take-off run C(NOx), µg/m³; 8 – measured NOx concentration during take-off run C(NOx), µg/m³

Figure 16   Comparison of measured and modelled noise levels, (a) and concentrations (b) of the pollutants (continued) (see online version for colours)
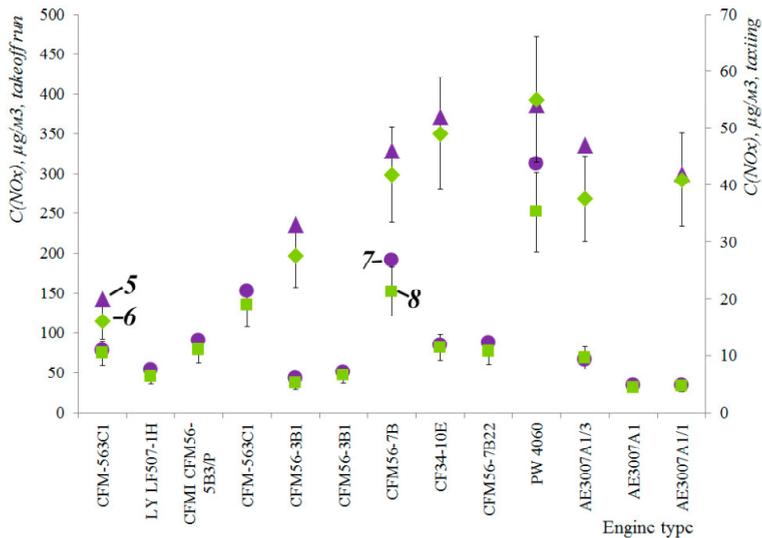
(b)

Notes: 1 – calculated *SEL*, dBA; 2 – measured *SEL*, dBA; 3 – calculated L_{Amax}, dBA;
4 – measured L_{Amax}, dBA; 5 – calculated NOx concentration during taxiing C(NOx), μg/m³; 6 – measured NOx concentration during taxiing, μg/m³;
7 – calculated NOx concentration during take-off run C(NOx), μg/m³;
8 – measured NOx concentration during take-off run C(NOx), μg/m³

The results of the measurements allow us to validate noise and pollution models in the vicinity of the airport IsoBella (analogue INM, FAA, USA) and PolEmiCa (analogue of Emission Dispersion Modelling System EMDS, FAA, USA). The comparison of measured and modelled noise levels and concentrations of pollutants has shown that correlation coefficients are rather high (0.9…0.99) (Figure 16).

5   Conclusions

Aircraft noise and local air quality has been regarded as the major environmental issues related to airports. Many airports have introduced a variety of measures to assess and reduce their impact, where the assessment plays fundamental role as for exposure analysis, so as for further impact of these factors on population or/and ecosystem under the control.

Meanwhile, the ADS-B position tracking system has quickly risen in popularity – FlightRadar24 flight tracking website is an example of the usage of this technology for surveillance by people for a number of purposes. The system is portable and compact, and the unified streams of data can more fully characterise an individual aircraft in flight or/and on the ground, offering distinct advantages over existing monitoring systems. The use of ADS-B data for the computation of AN and LAQ around airports is still a research topic for the authors, who focused on the extensive exploitation of ADS-B data available on the web and from their tuners for each flight event. The aircraft performance,

necessary for the AN and LAQ computations, may be estimated by analysis of ADS-B data sets (aircraft position and speed) and further synthesis of flight procedures for every flight event (the reconstruction of flight events to be used for the prediction of the noise levels or footprints for them, and for air pollution also) in accordance with methodology of ICAO Doc 9911 (2018) and ECAC Doc 29 (2016) for AN, ICAO Doc 9889 – for LAQ around the airport.

This paper presents an important upgrade of a modelling tool devised by the authors for estimating AN and LAQ around civil airports, which is based on a best-practice AN and LAQ computation methods and flight tracking data collected from the ADS-B data streams and complemented by datasets of aircraft models, airport (aerodrome) layout, and terrain features. Targeting more accurate AN and LAQ predictions, the upgraded model introduces reasoned degrees of freedom in the flight procedures, and the tracked altitudes and speeds of each flight event are used to fit these procedures, which leads to more accurate calculation and analysis approach. Better predictions can be achieved by providing them with high-quality input data available from ADS-B data streams. Moreover, AN and LAQ impacts may be reduced by introduction of the novel technologies in aircraft operation, for example if the ADS-B data will be used for assessment how correctly the flight procedures were realised, making the aircraft operation more sustainable.

Noise contours simulating along nominal routes (ground tracks from the AIP) and standard take-off/landing profiles embedded in modern noise modelling systems (AEDT, INM, IsoBella), in comparison with noise contours along the trajectories of aircraft traffic, obtained from the results of ADS-B observations, can significantly differ in area and shape: both close to the aerodrome (for levels $L_{Amax} = 85$ dBA), and for large distances from the ends of the runway (for levels $L_{Amax} = 60$–65 dBA). The accuracy of AN calculations is essentially higher (proved by comparisons between the measurements and calculations), so the consistency of the protection measures (for example, noise zoning) implementation should be stricter in advance.

Similar peculiarities of the ADS-B technology for LAQ assessment improvements are character also, but not for every flight event. And rather, for a clearer statistical description of emission sources during the year, taking into account the annual change in meteorological parameters (due to the importance for assessing the human impact of the average annual concentrations of dominant species in the air). ADS-B technology may fill a gap in the aviation emissions inventories, since it uses real-time flights and produces estimates at a very granular level.

References

Abhyankar, V.V., Gavade, S.A. and Bhole, K.S. (2019) 'System development for simultaneous measurement and control of pH and moisture of soil', *2019 International Conference on Nascent Technologies in Engineering (ICNTE)*, pp.1.5, doi: 10.1109/ICNTE44896.2019 .8946049.

Directive 2002/49/EC of the European Parliament and of the Council of 25 June 2002 relating to the assessment and management of environmental noise, Official Journal of the European Communities, L189/12-25, 18 July 2002.

DSTU-N B V.1.1-31, 2013 (2014) *Protection of Territories, Buildings and Structures from Noise*, National Standard of Ukraine ДСТУ-Н Б В.1.1-31:2013, Ukrainian.

ECAC Doc 29 (2016) *Report on Standard Method of Computing Noise Contours around Civil Airports*, 4th ed., Vols. 1–3, ECAC.CEAC Doc 29.

ICAO Doc 9829 (2004) *Guidance on the Balanced Approach to Aircraft Noise Management*, 1st ed., ICAO Doc 9829, ICAO.

ICAO Doc 9911 (2018) *Recommended Method for Computing Noise Contours Around Airports*, 2nd ed., ICAO Doc 9911, ICAO.

ISO 1996-1 (2016) *Acoustics — Description, Measurement and Assessment of Environmental Noise — Part 1: Basic Quantities and Assessment Procedures*, ISO Central Secretariat, Vernier, Geneva, Switzerland [online] https://www.iso.org/standard/59765.html (accessed 25 August 2022).

ISO/CD 20906 (2009) *Acoustics—Unattended Monitoring of Aircraft Sound in the Vicinity of Airports*, ISO Central Secretariat, Vernier, Geneva, Switzerland [online] https://www.iso.org/standard/35580.html (accessed 25 August 2022).

Konovalova, O. and Zaporozhets, O. (2021) 'Noise protection zones around Ukrainian airports as an element of balanced approach to noise control', *International Journal of Sustainable Aviation*, Vol. 7, No. 3, pp.187–202, https://doi.org/10.1504/IJSA.2021.119175.

National Academies of Sciences, Engineering, and Medicine (2009) *Enhanced Modeling of Aircraft Taxiway Noise, Volume 1: Scoping*, The National Academies Press, Washington, DC, https://doi.org/10.17226/22992 (accessed 25 August 2022).

National Academies of Sciences, Engineering, and Medicine (2013) *Enhanced Modeling of Aircraft Taxiway Noise, Volume 2: Aircraft Taxi Noise Database and Development Process*, The National Academies Press, Washington, DC, https://doi.org/10.17226/22606 (accessed 25 August 2022).

Report G 10.1 (2006) 'Expansion of the Frankfurt Airport', *Documents to the Plan Approval Proceedings, Part B, Examination of the Noise caused by Taxiing and Ground Noise*, 31 October, Planungsgemeinschaft BeSB – Obermeyer, Munich.

SAAU AR-381 (2019) *Requirements for Operators related to Noise Zoning of the Airport Vicinity*, 26 March, Ukrainian Aviation Rules, State Aviation Service of Ukraine (SAAU) [online] https://zakon.rada.gov.ua/laws/show/z0461-19?lang=en/ (accessed 25 August 2022).

SAAU Order 585 (2020) *Methodical Instructions on Airport Vicinity Zoning according to Noise Conditions*, 23 April, State Aviation Service of Ukraine [online] https://avia.gov.ua/wp-content/uploads/2019/10/Nakaz-585-Pro-zatverdzhennya-metodichnih-rekomendatsij-2.pdf (accessed 25 August 2022).

Schultz, M., Olive, X., Rosenow, J., Fricke, H. and Alam, S. (2020) 'Analysis of airport ground operations based on ADS-B data', *International Conference on Artificial Intelligence and Data Analytics for Air Transportation*, Singapour, Singapore, pp.1–9.

SSR-173 (1996) *State Sanitary Rules for Planning of Inhabited Localities*, 19 June, Order of Ministry of Health No. 173 [online] https://zakon.rada.gov.ua/laws/show/z0379-96#Text.

Sweriduk, G.D., Cheng, V.H.L. and Foyle, D.C. (2011) 'Models for aircraft surface operations environmental analysis', paper presented at the *11th AIAA Aviation*.

Synylo, K. and Kazhan, K. (2014) 'Monitoring of air pollution produced by aircraft in the vicinity of airport', *Proceedings of the National Aviation University*, Vol. 61, No. 4, pp.153–161.

Synylo, K., Kurtenbach, R., Wiesen, P. and Zaporozhets, O. (2015) 'Measurement of aircraft engine emissions inside the airport', *The 4th International Conference on Transport, Atmosphere and Climate, June 2015: Proceedings*, – Bad Kohlgrub, Germany, pp.28–33.

Synylo, K., Kurtenbach, R., Wiesen, P. and Zaporozhets, O. (2016) 'Comparison of measured and modelled NOx concentrations in the plumes from aircraft engines for take-off conditions', in *Proceedings of 2nd International Symposium on Sustainable Aviation*, Istanbul, Turkey.

Synylo, K., Ulianova, K. and Zaporozhets, O. (2021) 'Air quality studies at Ukrainian Airports', *International Journal of Aviation Science and Technology*, Vol. 2, No. 1, pp.4–14.

Zaporozhets, O. and Blyukher, B. (2019) 'Risk methodology to assess and control aircraft noise impact in vicinity of the airports', in Karakoc, H., Colpan, C., Altuntas, O. and Sohret, Y. (Eds.): *Sustainable Aviation*, pp.37–79, Springer International Publishing, https://doi.org /10.1007/978-3-030-14195-0_3.

Zaporozhets, O., Gulevets, V., Karpenko, S., Kazhan, K., Konovalova, O. and Paraschanov, V. (2021) 'Aircraft noise measurements in Ukrainian airports', *ISEAS'21 (International Symposium on Electric Aircraft and Autonomus Systems) Program*, 16–18 December, Eskisehir, Turkey.

Zaporozhets, O., Tokarev, V. and Attenborough, K. (2011) *Aircraft Noise: Assessment, Prediction and Control*, Glyph International, Taylor & Francis.

Nomenclature

ADS-B	Automatic Dependent Surveillance-Broadcast
AIP	Aeronautical Information Performance
AN	Aircraft Noise
ECAC	European Civil Aviation Conference
END	Environmental Noise Directive
ICAO	International Civil Aviation Organization
GPS	Global Positioning System
LAQ	Local Air Quality
LTO	Landing and Taking-Off
MP	Measurement Point
SEL	Sound Exposure Level.