Web data for computing real-world noise from civil aviation

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ABSTRACT

A large amount of data on civil air traffic is now available on the web, thanks to the recent development of flight tracker websites. This paper presents a novel methodology to exploit these data for computing real-world noise around airports. The proposed approach consists of data collection and pre-processing, flight path reconstruction, aircraft noise computation using a best-practice model (ECAC Doc.29), and rendering of ground track and noise contour maps in airport areas. Applications are shown for nine European airports, where the daily air traffic reconstructed from 10,752 collected flights compares well with official records from EUROCONTROL. Among these airports, London Heathrow, Amsterdam Schiphol and Vienna-Schwechat have been considered for the validation of the present methodology, and a good agreement is found between predicted ground noise levels and available historical data, with the largest deviations being detected in the portions of the airport areas most affected by departure events. The present work constitutes the first step to harnessing the potential of web data in aviation, unlocking unprecedented possibilities for assessing the environmental impact of civil aviation and providing policy-makers with a powerful tool for developing guidelines and regulations aimed at mitigating the detrimental effects of air traffic in densely inhabited regions.

Nomenclature

Symbols
All symbols in the equations are defined in the text.

Acronyms
ADS-B Automatic Dependent Surveillance – Broadcast
AEDT Aviation Environmental Design Tool
ANCON Aircraft Noise Contour (noise prediction model)
ANP Aircraft Noise and Performance
API Application Programming Interface
ARP Airport Reference Point
ASL Above Sea Level
ATC Air Traffic Control
DDR2 Demand Data Repository, version 2
ECAC European Civil Aviation Conference

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1. Introduction

Scheduled air transport accounted for about 3.8 billion passengers in 2016, with a 6.8% increase compared to 2015, and a global operating fleet of more than 28,000 aircraft (ICAO, 2016). In the same year, passenger and weight load factors are reported to be 80% and 67%, respectively, with higher values in Europe and North America. Non-scheduled air transport is estimated to represent no more than 4% of the total civil air traffic, with a relative impact that has been decreasing since 2007. Air traffic forecasts for the next 20 years (Boeing Commercial Airplanes, 2017) suggest that commercial operations will be steadily growing in terms of both passengers (+4.7% per year) and fleet (+3.5% per year), driven primarily by the economic growth in Asia and Africa. The worldwide number of aircraft in operation is expected to reach 47,000 units by 2036, with single-aisle airplanes accounting for around 70% of the total.

Current air traffic has a strong impact on the environment, in terms of both air pollutant emissions and noise. It was estimated in 2010 that around 8000 premature deaths per year worldwide are caused by aircraft cruise emissions (Barrett et al., 2010), while aviation noise has long been acknowledged to affect negatively the wellbeing of people living close to airports (Lawton and Fujiwara, 2010), especially children (Hygge et al., 2002). In order to limit the environmental impact of present and future air transport, ambitious objectives and political agendas have been set in the past 20 years, among which are the NASA N + 3 (Collier, 2012) and the EU’s Flightpath 2050 (European Commission, 2011). The latter aims to reduce CO₂ emissions by 75%, NOₓ emissions by 90% and perceived noise by 65% by the year 2050 in comparison to the average new aircraft delivered in 2000. As the use of larger airliners in place of single-aisle airplanes is hindered by market needs (Givoni and Rietveld, 2009), in the upcoming decades the industry will be centred around the evolution of narrow-body aircraft, and a number of concepts have already been presented (Graham et al., 2014). Concerning noise, the ICAO standards were introduced in 1972 and their evolution with the aviation technical developments since then (Dickson, 2015) have already led to a significant reduction in aircraft noise (Astley, 2014). Further improvements have also been achieved thanks to specific noise abatement measures applied by several airports (Ganic et al., 2015). Future actions for noise reduction are expected to target airframes (Li et al., 2013) and propulsion systems (Leylekian et al., 2014), besides an improved management of take-off, landing and taxiing procedures (Netjasov, 2012).

Any effective measure to counteract aircraft noise requires assessing its impact in airport areas. This is usually done by using noise prediction models, which can be classified in two categories, i.e., theoretical methods and best-practice methods (Filippone, 2014). Whereas theoretical methods, based on physical models of sound generation and propagation, provide very accurate results at the cost of high computational burden, best-practice methods rely on measurement databases and simple sub-models to enable much faster predictions. Therefore, the latter are widely adopted by civil aviation operators to obtain noise contour maps in airport areas. Current examples are AEDT in the US, ANCON in the UK, FLULA in Switzerland, and ECAC Doc.29 model in the EU (European Civil Aviation Conference, 2016a); other simplified models targeting further decrease in computational burden have recently been proposed (Li et al., 2015; Torija et al., 2017).

A key input for these noise models is the air traffic data, with special reference to flight patterns in the proximity of airports. Whereas such information has been difficult to obtain in the past, the recent development of the Internet and the widespread installation of ADS-B transponders on aircraft (mandatory by 2020 for large aircraft operating within the European airspace (European Commission, 2017)) have significantly facilitated the public accessibility of such data. As a consequence, websites called “flight trackers” have gone online, aimed at providing their users with aircraft operation data in real time. Examples include Flightradar24 (Flightradar24), FlightAware (FlightAware), RadarBox24 (AirNav RadarBox24) and Plane Finder (Plane Finder: Flight Tracker), which collect and interpret data from thousands of ADS-B receivers located all over the world, as well as information from radars and other data link sources. In addition, other websites provide extensive information on aircraft models (e.g., Airlinerlist (Airlinerlist.com), Airfleets (Airfleets aviation)) and general airport specifications (e.g., OurAirports (Megginson, 2018)). Combining and reorganising such data can lead to the full characterisation of flight events, enabling an appropriate aircraft noise model to generate noise contour maps.

Although ADS-B information has already been used for assessing aircraft noise around single airports (Gagliardi et al., 2017; Nguyen et al., 2016), an example of large-scale exploitation of web data for computing daily noise contour maps at multiple airports is only a recent achievement (De Gennaro et al., 2018). In that study, a real-time web data collection produced information on 36,302
flights, from which 30,660 flight operations in 391 airports (mostly in ECAC member countries) were identified and used to compute daily noise maps by means of the ECAC noise model. Although intercontinental departures were not retrieved (departure events were recovered from the flight histories of arrived aircraft), the feasibility of a large-scale noise prediction based on web data was effectively confirmed.

Following this “proof of concept”, the present paper reports an improved version of the original approach, which has been reformulated and structured in a leaner and more robust procedure. Changes have been made to the web data collection, which now focuses on single airports by retrieving departures and arrivals independently of each other, and to the process of flight path reconstruction. In addition, the latest release of ECAC Doc.29, published in late 2016 (European Civil Aviation Conference, 2016a), and an updated Aircraft Noise and Performance (ANP) database, made available in 2018 (EUROCONTROL, 2018), have been implemented. Based on these improvements, the retrieval of flight data, the reconstruction of single flight operations, and the calculation of the noise contour maps in airport areas are made more reliable and accurate.

The paper is organised as follows. Section 2 reports the complete procedures of web data collection and processing, with special emphasis on how the flight information is made usable as input to the ECAC noise model. Details are then provided on the application of the ECAC model to the computation of ground track, flight profile, flight path, and noise of single flight events (departures and arrivals), which provides a basis for calculating daily cumulative noise metrics in airport areas. In particular, a thorough description is given of the proposed algorithm for the computation of the ground track, which is shown to be effective even in case of convoluted flight trajectories. The results of the present work, reported in Section 3, include a comparison of traffic figures and aircraft fleet with EUROCONTROL official data, and the ground track and LEQn contour maps predicted in nine European airports, three of which are discussed in detail. Conclusions and future developments are presented in Section 4.

2. Methodology

The proposed approach consists in retrieving big data of civil aircraft fleet and movements from the web, interpreting and processing them to reconstruct flight events, and using such events as an input to the ECAC noise model to compute ground noise footprints around airports. The entire procedure, from data collection to noise computation, is described in Sections 2.2–2.5. A brief preliminary description of the ECAC noise model is provided in Section 2.1, since the model requirements influence the operations reported in the subsequent sections.

2.1. ECAC noise model and ANP database

The ECAC noise model is a best-practice segmentation model for the prediction of aircraft noise around airports. The fourth and latest version of this model was published by ECAC in December 2016 (European Civil Aviation Conference, 2016a,b,c). The model allows the generation of aircraft noise contour maps by superposing the effects of single flight events, i.e., departures and arrivals. For each event, the model computes the sound level at specified receiver locations by superposing the contributions of individual noise-emitting units obtained by segmenting the flight path. The computation of a flight path requires the knowledge of the aircraft position coordinates during the event, which in the present work are retrieved from dedicated websites, i.e., flight trackers.

Besides information on the flight trajectory, the ECAC model requires data on aircraft (model, weight, number of engines, aerodynamic and engine parameters, etc.), flight procedures, and reference sound values. These latter are known as NPD values and consist of noise event levels expressed as a function of the aircraft-receiver distance at specified engine power settings. All these pieces of information can be found in the ANP database (EUROCONTROL, 2018), which organises them into a set of tables referring to a limited number of proxies. The ANP database contains data for almost 140 proxies, and the information about one of them is accessed by specifying flight procedure, noise metric, and, in case of departures, the trip length.

About aircraft, the data extracted from the web enables retrieval of up to two different pieces of information per flight, namely an ICAO aircraft type designator (a four-character code, such as B738 for various Boeing 737–800s) and an aircraft model (e.g., A320-216). ANP provides two aircraft substitution tables to associate such pieces of information with a proxy. In the first table the aircraft model is mapped to a proxy, which is associated with two noise correction factors (“number of equivalent departures” and “number of equivalent arrivals”). These factors express the ratio of the sound intensities of the actual aircraft model and its proxy for departure and arrival operations, thus allowing ANP to reflect the extremely large variety of aircraft models around the world with a limited number of proxies. If only the ICAO designator is known, the second substitution table is used to select the proxy; in this case the correction factors represent the noisiest aircraft configuration available in ANP for that designator. Further procedural details are provided in Section 2.3.

The application of the ECAC model and the access to the ANP tables require knowledge of the following data for a departure/arrival flight event:

1. date, time, and location of the event;
2. information on the aircraft model/type;
3. an ordered series of a sufficiently large number of aircraft positions.

Meeting the first requirement allows associating the event with the correct airport and time slot, while the other ones enable the computation of flight path and noise levels. The operations described in the following two sections, that is data collection and processing, have been performed to fulfil, when possible, these three requirements.
2.2. Data collection procedure

The primary source of air traffic data considered in this work is flight tracker FlightAware (FlightAware), a website that reports aircraft movements around the world by gathering data from different devices (ADS-B transponders, radars, etc.) and sorting them so as to rebuild entire flight histories. The data provided by FlightAware for each flight history are organised in tables, the rows of which report consecutive aircraft states, typically spaced by 15 s, in terms of latitude, longitude, altitude and speed. If searched by airport, FlightAware returns tables of departures and arrivals at the selected airport, the entries of which contain links to single flight histories. In addition, FlightAware reports the ICAO aircraft type designator, the aircraft registration number, and, for scheduled flights, the ICAO airline designator and flight number (e.g., UAL880). Rarely, one or more of these data are missing, and at times the IATA aircraft type designator is reported in place of the ICAO one.

Making use of FlightAware’s FlightXML 3.0 API (the website offers a monthly tiered subscription to this API) a data collection program was built to retrieve the time histories of flights that start or end at a selected airport. The portions of these flight tables that refer to take-off or landing operations will constitute the noise-generating flight events to be processed by the ECAC model. The program searches one airport at a time on a given day and retrieves the movement history, designators and registration numbers of each aircraft that landed at or took off from that airport, taking note of the type of event (departure or arrival) with specific labels. The aircraft registration number will be used to identify the aircraft model, whereas specific portions of the flight histories will be interpreted to generate the complete departure and arrival trajectories.

For each flight, the collection program retrieves first departure and arrival airports, dates and times of the events (in both local and GMT time zones), all aircraft and airline designators and numbers, and distance flown. Then, the program uses FlightXML to collect specific data on the flight history, i.e., latitude, longitude, speed and altitude, all referring to GMT times. In the end, the full set of information pertaining to the flight is rearranged, gathered into a single file and stored in a database. As an example, a portion of a typical file is shown in Fig. 1.

The program for data collection was used to retrieve daily flight events in nine European airports. About 10,700 flight histories were collected, including a few departure/arrival events occurred shortly before or after the targeted day to ensure full coverage of the entire 24-hour period. The average flight history contains about 1,800 different pieces of information, and all the flights together account for around $2 \times 10^7$ pieces of information stored in approximately 140 MB. There is, however, no theoretical limit to the number of airports or days that can be searched, and the program is able to retrieve all the recorded flight histories around the world if enough hardware resources are available.

2.3. Data organisation and pre-processing

The data collection procedure produces a large number of files that usually contain all the information required by the ECAC noise model. However, three major issues have to be addressed before this information can be extracted and used for noise computation:

![Fig. 1. Example of flight table based on raw data from flight trackers.](image-url)
(1) some data from FlightXML need to be rearranged, in particular arrival dates and times (sometimes unclear, a few times missing) and altitudes (reported in hecto-feet);
(2) the data displayed at the top or bottom of the flight table are often unreliable, because aircraft positions very close to the landing or take-off runway are either missing or inconsistent with reasonable flight paths;
(3) information on aircraft models does not comply with the syntax of the ANP substitution tables.

To solve these problems, suitable pre-processing routines were developed to check, correct, sort and standardise the raw flight data. The data processing is performed in two steps: (i) the aircraft registration number is translated into an aircraft model that can be handled by the ANP substitution tables, and (ii) flight movements and aircraft models are interpreted, translated according to ECAC and ANP requirements, and stored in new files with standardised format.

2.3.1. Identification of the aircraft model

Starting from raw data, the registration numbers are associated with the corresponding aircraft models to be used in the first ANP substitution table for the proxy association. To perform this conversion, an aircraft model database was built relying on data reported on website Airlinerlist (Airlinerlist.com). This site offers detailed airplane tables that contain data for more than a hundred thousand aircraft, including registration numbers, test registration numbers, construction numbers, aircraft models, and other general information (e.g., aircraft owners), lacking only an indication of the engine models. These tables were rearranged in order to make the aircraft model names compliant with the syntax of the ANP substitution tables. This enables a specific routine to read the aircraft registration numbers, if present, from the flight datasets, and then to retrieve the corresponding aircraft models in the aforementioned tables.

In the present application, over 95% of the flights had a registration number, and among them an aircraft model was found in all but a few cases concerning airplanes either extremely uncommon or re-registered after the last update of website Airlinerlist (21 May 2018) prior to the flight data collection (10–13 June 2018). In case no registration number was available, an equivalent aircraft model (proxy) could still be identified using ICAO or IATA designators (see next subsection).

2.3.2. Data pre-processing

After finding the actual aircraft models, the data processing proceeded with checking, cleaning up, and sorting the raw data files. These tasks were performed by a software module structured as detailed by the flowchart in Fig. 2.

The first operation is to check, for each flight, the presence of basic pieces of information (airport, date and time of the event, aircraft model and/or aircraft designator) and a minimum number of aircraft position data for the construction of a reliable ground track. In general, the failure of this check prevents the processing of the flight, which thus has to be discarded. However, in case the arrival date and time are unclear or unknown (for instance, there are empty cells in rows 10–11 and columns E-F-G of Fig. 1), they can be reliably rebuilt from flight history GMT times (column A, from row 16 onwards) and local time zones (cell B14).

The second operation is the translation of the aircraft model into one of the proxies listed in the ANP database, which also enables retrieving the values of the two noise correction factors mentioned in Section 2.1. This translation step generally follows the pattern described below:

(1) if just the aircraft model is available, use it in the first substitution table;
(2) if just the aircraft designator (ICAO or IATA) is available, use it in the second substitution table;
(3) if both pieces of information are known, use the aircraft model in the first substitution table; if no proxy is found, use the aircraft designator in the second substitution table;
(4) if there is no aircraft information, or it does not lead to a suitable ANP proxy, discard the flight.

Although using both conversion tools typically leads to the same proxy, the knowledge of the exact aircraft model (first table) enables a more precise selection of the noise correction factors. The latter depend mainly on the aircraft model, and secondarily on engine model and maximum aircraft weight. For the same aircraft model, the first ANP table lists a number of possible weight/engine configurations with the corresponding correction factors, but the flight trackers do not provide any information on the specific configuration of the aircraft that performs a given flight. Furthermore, it is very difficult, if not impossible, to recover the exact configuration by starting from the aircraft registration number provided by the flight tracker. Therefore, the correction factors for departures and arrivals pertaining to different configurations of the same aircraft model were averaged and their mean values were associated with the aircraft model, without any distinction among different variants. From the first ANP table, it was estimated that about 95% of the aircraft models exhibit a maximum noise level deviation of 4 dB between the noisiest and quietest engine/weight configurations. Therefore, using the mean values of the correction factors for a given aircraft model should lead to a maximum error of about ±2 dB in the estimation of the sound intensity levels of most aircraft. Furthermore, it should be considered that the effects of such an inaccuracy are further weakened when computing cumulative noise metrics around airports, which is the main concern of the present work.

Finally, in a few edge cases (e.g., private jets, small aircraft, etc.) aircraft information was available, but the aircraft model was not included in the ANP substitution table. To avoid discarding potentially relevant flight events, the missing aircraft models were added manually to the first ANP table and associated with proxies having the most similar characteristics to those of the actual aircraft (number, type, and position of engines, weight, size), and unitary values were assigned to their noise correction factors.

The third operation is the assignment of either the departure or the arrival runway at the considered airport, and the
reconstruction of the take-off or landing path. In fact, the problem mentioned at point (2) in Section 2.3 turned out to occur quite frequently, which caused all flight positions very close to runways to be considered as unreliable information. After retrieving the geographical coordinates of the runways from website OurAirports (Meggison, 2018), the most suitable runway (if more than one) at
a given airport is assigned to the flight event according to the following procedure. First, the airborne point closest to the airport is found, and then the angle is computed between the direction of each runway and the segment joining its mid-point with the projection on the ground of the airborne point (see Fig. 3). The smallest of these angles marks the most likely runway, which is finally assigned to the event. However, if the first airborne point is very far away from the airport (more than 80,000 ft), the assignment is performed randomly, since there is not enough information to make reliable assumptions.

After the runway has been selected, three points on that runway are added at the top or bottom of the flight table for a departure or an arrival, respectively, in order to ensure a straight movement on the ground. The location of these points depends on the type of event. In case of a departure, the first point (start of take-off) is placed at a distance from the runway starting point that decreases with growing aircraft weight. The latter is retrieved in the ANP database, where each proxy is given a set of default take-off weights depending on trip length. The second point is placed at 75% of the runway length, which accounts for the take-off distance of even the heaviest aircraft (see ECAC Doc.29 Vol. 2 (European Civil Aviation Conference, 2016b) for the computation of the take-off length), while the third point is placed between the other two points. For an arrival, the last point (end of landing) is placed at the position where the aircraft ends the deceleration procedure prescribed by ECAC. The other two points are placed close to the landing threshold (position on the runway beyond which the aircraft is allowed to touch the ground) to ensure a straight deceleration path.

The last operation is the rearrangement of the flight data. ANP proxy information is added to the file, the flight history table is modified to accommodate the three new runway points, altitudes are converted to feet, and some unnecessary data (e.g., departure or arrival GMT times) are erased. In the end, the corrected file for a specific flight is stored in a new database. An example of a processed file is given in Fig. 4.

The data processing program performed the above operations for all the collected flights. About 99% of the files were checked, corrected and standardised, resulting in usable inputs for the ECAC noise model. The two main reasons that caused flights to be discarded were unknown aircraft (not even an ICAO/IATA aircraft designator was reported) and too little information in the flight table.

### 2.4. Implementation of the ECAC noise model

The computation of the aircraft noise generated at specified locations by a single flight event was performed according to ECAC Doc.29 Vol. 2 (European Civil Aviation Conference, 2016b). Before describing the implementation of the ECAC noise model, its general structure and terminology are presented below in order to introduce the computational steps detailed in Sections from 2.4.1 to 2.4.4.

The ECAC noise model is a so-called “segmentation” model, which means that the aircraft noise caused by a single flight event is computed by superposing the contributions of single sound-emitting units called flight path segments. A flight path segment represents a limited part of the aircraft trajectory, at the end-points of which all the flight geometric and operational parameters are defined. A set of flight path segments forms a segmented flight path, which is the representation of the entire aircraft motion during the flight event.

The complete definition of a flight path requires specifying the projection on the ground of the aircraft trajectory, called ground track, and the aircraft motion in the vertical plane, called flight profile. The ground track is approximated by a sequence of straight segments and circular arcs, the end-points of which are identified by Cartesian coordinates and curvilinear abscissa s. In contrast, the flight profile is not simply a geometric entity, but it represents a sequence of aircraft heights above the ground track resulting from
either the analysis of aircraft movement data or the application of a set of standardised flight procedures, called procedural steps. Therefore, the end-points of each flight profile segment are associated with flight operational parameters such as aircraft altitude, speed, bank angle, and engine power setting, the knowledge of which is essential to noise computation.

According to ECAC, a complete flight path can be generated either by synthesis from sets of standardised procedures concerning both ground track and flight profile, or by analysis of aircraft movement data such as those provided by the flight trackers. However, a 15-second spacing between consecutive aircraft states and the possible absence of information about altitude and speed do not allow a reliable generation of flight profiles from aircraft movement data. Therefore, only ground tracks are computed via flight data analysis, whereas flight profiles are synthesised relying on the procedural steps listed in the ANP database.

The segmented flight path is obtained by overlaying the flight profile onto the ground track, resulting in a 3-D sequence of segments. After computing the flight path, the values of aircraft position and speed, engine power and bank angle at the ends of each segment are entered in appropriate equations, which finally provide the single event noise levels at specified receiver positions.

The procedure outlined above has been implemented in a computer program that provides the noise levels of a single flight event by performing the following operations:

(1) calculate the ground track via flight data analysis;
(2) calculate the flight profile by synthesis from ANP procedural steps;
(3) merge ground track and flight profile to obtain a segmented flight path;
(4) calculate the sound levels generated by each segment at specified ground locations;
(5) superpose the effects of all segments to obtain the final noise levels at those locations.

The computer program executes these five steps as described in Sections from 2.4.1 to 2.4.4 and according to the following assumptions:

- standard air temperature and pressure at 0 m ASL (i.e., 15°C and 101,325 Pa), scaling with altitude in accordance with the US standard atmosphere (National Oceanic and Atmospheric Administration, 1976);
- constant 8-knot headwind for both departures and arrivals.

### 2.4.1. Ground track construction

Given a flight event, the aircraft positions provided by the flight tracker along with the additional points placed on the runway...
represent the “original points” from which the ground track (GT) is constructed. For both departures and arrivals, the first GT point is assumed to lie on the runway, while an aircraft position sufficiently far away from the airport (distance $\geq 3 \times 10^5$ ft or altitude $\geq 2 \times 10^4$ ft) is selected as the last GT point, thus ensuring that the ground track is long enough to accommodate any synthesised flight profile. Latitude and longitude of the aircraft positions are converted into Cartesian coordinates using Vincenty’s formulae (Vincenty’s Formulae, 2018) and assuming the Airport Reference Point (ARP) as the origin of the coordinate system.

The procedure adopted for the GT construction consists of the five steps described below.

(1) The $N$ original points are connected by vectors $v_i$, $i = 1, \ldots, N - 1$ according to their sequence. The value and sign of angle $\alpha_i$ formed by consecutive vectors $v_{i-1}$ and $v_i$ are computed from the scalar and vector products of those vectors, resulting in

$$
\alpha_i = \text{sign}(v_{i-1} \times v_i) \cos^{-1} \left( \frac{v_{i-1} \cdot v_i}{|v_{i-1}| |v_i|} \right), \quad i = 2, \ldots, N - 1
$$

Note that formula (1) returns angles $[\alpha, \pi]$, and hence the aircraft turning direction (left or right).

(2) The first angle between vectors $v_1$ and $v_2$ is compared with a user-defined threshold value, $\alpha_0$ ($\alpha_0 = 2^\circ$ in the present work). If $|\alpha_1| < \alpha_0$, then points 1, 2 and 3 are considered to be part of a straight segment, and the check is repeated for following angles $\alpha_i$, $i > 2$, until condition $|\alpha| \geq \alpha_0$ is met. In this case point $P_i = i$ is assumed to be the starting point of a circular arc, the extension of which is determined by checking if the following conditions are met by the points that follow $P_i$:

(a) $|\alpha| \geq \alpha_0,$

(b) $\sum_{j=P_i}^{P_{i+1}} |\alpha_j| < \theta_{\max},$

(c) $\alpha_{i-1}; \alpha_i > 0,$

(d) $i < N,$

where $\theta_{\max}$ is the user-defined maximum angle to be covered by a single arc ($\theta_{\max} = 70^\circ$ in this work). If any of conditions (2) is violated, the circular arc is ended.

(3) Radius $r$ and coordinates $(x_C, y_C)$ of centre $C$ of the circular arc are computed from the coordinates of points $P_i$ and $P_e$, and angles $\alpha_j$, $j = P_i + 1, \ldots, P_e - 1$. If there is only one point $P_j$ between $P_i$ and $P_e$ (see Fig. 5(a)), simple geometrical considerations lead to the expressions:

$$
r = \frac{P_i P_e}{2 \sin |\alpha_i|}, \quad x_C = x_M - \frac{y_B - y_M}{\tan \alpha_i}, \quad y_C = y_M + \frac{x_B - x_M}{\tan \alpha_i}
$$

where $x_M$ and $y_M$ are the coordinates of mid-point $M$ of segment $P_i P_e$. If there are two or more points between $P_i$ and $P_e$, central angle $\theta_j$ of the arc passing through $P_i, P_j$ and $P_e$ is computed for each intermediate point $P_j$ ($\theta_j = 2\alpha_j$). Then, the average central angle,

$$
\bar{\theta} = \frac{1}{P_e - P_i - 1} \sum_{j=P_i+1}^{P_e-1} \theta_j
$$

is used to compute the radius and centre coordinates of an “average circular arc” by simply setting $\alpha_j = \bar{\theta}/2$ in Eq. (3). This approach produces results comparable to those of a least square circular arc interpolation, but it is much simpler. Finally, if there is no point between $P_i$ and $P_e$, imposing the passage of the circular arc through points $P_i$ and $P_e$ and the tangency condition at one of the two end-points provides unrealistic results in many cases. Therefore, a biarc interpolation algorithm (Juckett, 2018) is applied, which generates two circular arcs tangent to each other and to the neighbouring segments.

(4) The circular arc determined at point (3) is split into a number of segments according to the segmentation requirement of the flight path, and hence of the ground track. Each segment is the chord of a sub-arc that subtends a central angle, $\Delta \theta$, defined by the user ($\Delta \theta \equiv 5^\circ$ in the present work).

\[Fig. \text{5.} \text{ (a) Construction of a GT circular arc with one point } P_j \text{ between } P_i \text{ and } P_e, \text{ and (b) a GT portion close to a runway corrected via data removal.}\]
(5) Steps from (2) to (4) are repeated until $i = N - 1$.

The ground track obtained from the above procedure consists of a sequence of straight segments, some of which approximate circular arcs of known radii and centres, while the remaining ones simply connect the end-points of consecutive circular arcs. In some cases, the initial portion of the ground track (close to the runway) exhibits arcs with very small radii, which do not agree with a reasonable flight path. This is usually due to small errors in ADS-B data generated by aircraft without GPS transmitters (NLR, 2016). In such cases, the whole procedure for the ground track construction is repeated removing one airborne point at a time until realistic radii (at least 1,500 ft) are obtained. Fig. 5(b) provides an example of such a correction. Point $R$ is removed as it does not allow for a reasonable track, causing $P_s$ and $P_e$ to be smoothly connected via biarc interpolation.

To summarise, the following data are known for each segment composing the ground track:

- Cartesian coordinates $(x, y)$ of the segment end-points;
- Radius of the circular arc approximated by the segment (for segments that represent a straight path a very large value, $10^8$ ft, is set);
- Value and sign of the central angle subtended by the circular sub-arc;
- Curvilinear abscissa (or “ground coordinate”, $s$) of the segment end-points along the GT.

2.4.2. Flight profile construction

The flight profile is computed from a sorted sequence of ANP procedural steps that describe the pilot’s selections of engine thrust, flap angle, and acceleration or vertical speed to achieve certain targets (speed and/or height). When coupled with flight mechanics equations and atmospheric models, this sequence results in a set of operational parameters defined at the end-points of segments in the vertical plane $(s, z)$, $s$ being the ground coordinate and $z$ the height. Some details on the ECAC procedure for the synthesis of the flight profile are given in Appendix A. Fig. 6 shows an example of flight profile construction in terms of aircraft altitude, $H$, groundspeed, $V$, and corrected net thrust, $F_n/\delta$, along the ground track.

In order to make the synthesis of the flight profile independent of the ground track, the ECAC procedure neglects the effects of the aircraft bank angle (angle between wing and horizontal planes) needed to fly curved portions of the ground track. In principle, bank angles should affect the force balance equations in the flight profile calculation, but neglecting this influence leads to a markedly simpler and faster computation at the expense of a slight loss of accuracy. However, the information on the bank angles is essential to noise computation, and therefore it has to be recovered in the subsequent stage of flight path construction.

2.4.3. Flight path construction

The segmented flight path is the full representation of the whole aircraft motion during the flight event. It is obtained by merging the geometrical and operational properties of the end-points of the GT segments and flight profile sub-segments, as detailed in Appendix B. The flight path construction results in a sequence of straight segments in space, at the end-points of which the following variables are known:

Fig. 6. Flight profile of an A320-211 departing from Heathrow. Whereas altitude and speed increase with the ground coordinate, the corrected net thrust decreases sharply. After the take-off and stabilises for $H > 3000$ ft.
Cartesian coordinates \((x, y, z)\);
- calibrated airspeed \(V_C\), true airspeed \(V_T\), and groundspeed \(V\);
- corrected net thrust of one engine \(P = F_E/\delta\);
- bank angle \(\varepsilon\).

The number of flight path segments mainly depends on ANP proxy, flight operation, and convolution of the ground track. The extension on the ground of the flight path is determined by the completion of all the procedural steps that describe the flight event. The GT segments that lie beyond the last point of the flight profile do not contribute to the flight path, but they were retained for a complete representation of approach and departure routes, as shown in Section 3.

Fig. 7 shows the segmented flight path and the ground track for the same departure event reported in Fig. 6. The dashed vertical lines and triangles represent the projections of the GT points onto the flight path, while the inverted triangles denote the end-points of the flight profile sub-segments.

2.4.4. Noise computation for a single flight event

At a specified location on the ground (sound receiver, or “observer”), the noise generated by a single flight event can be suitably quantified by two noise metrics, i.e., the A-weighted sound exposure level, \(L_{AE}\) (also known as SEL), and maximum sound level, \(L_{A\text{max}}\).

In the ECAC noise model the whole flight event is split into \(N\) smaller events represented by the flight path segments, and each \(i\)-th segment is treated as an independent sound event that produces exposure level \(L_{AE,i}\) and maximum level \(L_{A\text{max},i}\). These sound levels can be easily computed by properly correcting baseline levels \(L_{AE,\text{Baseline}}(P, d)\) and \(L_{A\text{max,Baseline}}(P, d)\), which are the sound levels that the aircraft would produce at observer distance \(d\) when travelling with engine power \(P = F_E/\delta\) along an infinite straight path resulting from the extension of the \(i\)-th segment. The correction terms account for effects such as the acoustic impedance of moist air, lateral directivity due to engine installation and bank angle, sound wave reflection from the ground, finite segment length, start of roll directivity and reverse thrust, as specified in ECAC Doc.29 (European Civil Aviation Conference, 2016b).

After computing noise levels \(L_{AE,i}\) and \(L_{A\text{max},i}\) for all \(N\) segments, the overall exposure level is calculated by superposing the contributions of the \(N\) segments and accounting for the noise correction factor, \(N_{eq}\), introduced in Section 2.1:

\[
L_{AE} = 10\log_{10} \left( \sum_{i=1}^{N} 10^{L_{AE,i}/10} \right) + 10\log_{10}(N_{eq})
\]

whereas the maximum sound level is evaluated as

\[
L_{A\text{max}} = \max(L_{A\text{max},i}) + 10\log_{10}(N_{eq})
\]

2.5. Cumulative metrics and noise contours

Single event noise level \(L_{AE}\) can be used to compute time-weighted equivalent sound levels (cumulative noise metrics), which account for the overall acoustic energy released by multiple events over a given time period. The general equation for time-weighted levels is (European Civil Aviation Conference, 2016a)
Typical cumulative noise metrics for A-weighted sound exposure levels (European Civil Aviation Conference, 2016a).

<table>
<thead>
<tr>
<th>Name</th>
<th>( L_{A_{eq},W} )</th>
<th>( T_0 [s] )</th>
<th>( C )</th>
<th>( g_j )</th>
</tr>
</thead>
<tbody>
<tr>
<td>24-hour average sound level</td>
<td>( L_{A_{eq},24h} )</td>
<td>86,400</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>16-hour day-average sound level</td>
<td>( L_{A_{eq},day} )</td>
<td>57,600</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>8-hour night-average sound level</td>
<td>( L_{A_{eq},night} )</td>
<td>28,800</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Day-night average sound level</td>
<td>( L_{D NIGHT} )</td>
<td>86,400</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>Day-evening-night average sound level</td>
<td>( L_{D EVEN} )</td>
<td>86,400</td>
<td>0</td>
<td>( \sqrt{10} )</td>
</tr>
</tbody>
</table>

\[
L_{A_{eq},W} = 10 \log_{10} \left( \frac{T_0}{T_0} \sum_{j=1}^{N} g_j \cdot 10^{\frac{L_{A_{eq},j}}{10}} \right) + C
\]  

(7)

where \( L_{A_{eq},j} \) is the exposure level caused by the \( j \)-th event, and the summation is performed over all \( N \) noise events that occur during reference time period \( T_0 \). Coefficient \( g_j \) is a time-of-day dependent weighting factor, \( T_0 = 1 \ s \) for A-weighted exposure levels, and \( C \) is a normalisation constant. The values of \( T_0, C \) and \( g_j \) are given in Table 1 for each time-weighted level. The most widely used metric is the day-evening-night average sound level, \( L_{D EVEN} \), as it accounts for the whole 24-hour sound energy while penalising noise events at late hours, perceived as more annoying by the community. In particular, 5 dB(A) and 10 dB(A) are added to noise events occurring in the evening and at night, respectively. According to EU indications, a 12-hour daytime, from 7:00 to 19:00, and an evening duration of 4 h, from 19:00 to 23:00, are usually assumed, with night-time spanning the remaining 8 h.

Cumulative noise indices based on maximum sound levels are also defined by ECAC (European Civil Aviation Conference, 2016a), i.e., the average maximum sound level,

\[
\overline{L_{\text{max}}} = 10 \log_{10} \left( \frac{1}{N} \sum_{j=1}^{N} 10^{\frac{L_{A_{\text{max},j}}}{10}} \right)
\]  

(8)

and the absolute maximum sound level,

\[
L_{\text{max}} = \max(L_{A_{\text{max}}})
\]  

(9)

Furthermore, index Number Above Threshold (NATv) is defined as the number of noise events reaching or exceeding a threshold sound value \( X \) during a given time period.

In the present work, the noise levels of the daily events at a given airport are computed at a large number of grid points on the ground and employed to evaluate the cumulative noise metrics and indices at the same points. These cumulative values are used to draw noise contours on the physical map of the airport area. The contour maps are computed by processing the grid values of cumulative noise metrics and indices by means of Matlab routine contourf based on the Marching Squares algorithm.

The airport area, assumed to be flat, is covered by a square grid of equally spaced receivers, which extends for about 24.7 km (81,000 ft) in each of the four cardinal directions starting from the ARP. The receivers are spaced by about 457 m (1,500 ft) in both \( x \) and \( y \) directions, meaning that noise levels are available at 11,881 positions. The extension of the airport area (about 2,440 km\(^2\)) and the density of receivers were chosen as a trade-off between noise map resolution and computational burden.

3. Results

Data collection and noise level computations were carried out for daily flight events in nine European airports, chosen as noteworthy samples of air traffic in Europe. Among them are the largest airports on the continent (London Heathrow, Amsterdam Airport Schiphol, Paris Charles de Gaulle Airport, Frankfurt Airport), large airports of capitals (Rome Fiumicino Airport, Madrid-Barajas Airport, Vienna-Schwechat Airport), a medium Italian airport (Naples International Airport), and a small Italian regional airport (Trieste Airport – Friuli Venezia Giulia).

The targeted day for Amsterdam, Paris, Frankfurt, Rome, Madrid, Naples and Trieste airports was Monday, 11 June 2018. Flight events at Heathrow airport were collected on both Monday, 11 June and Wednesday, 13 June, because these two days experienced opposite wind directions, which markedly affect the local air traffic management. A similar choice was made for Vienna-Schwechat, where Sunday, 10 June and Tuesday, 12 June were targeted.

The computational time required to collect and pre-process the flight events was about 8 h, spread over the four days (10–13 June) and conditioned by the data retrieval speed limit of the flight tracker website. The computation of the noise levels at the selected airports took around 60 h using a 4-core CPU, but this time could be significantly reduced by parallelising the computation on more processors and possibly translating the computer codes from language Python, as used here, to a compiled programming language.

In this section, the maps of cumulative noise level \( L_{D EVEN} \) and the ground tracks of all daily flight events, calculated using the present methodology, are reported for each airport. They are superimposed onto physical maps of the territory, and the scale of the
Section 3.1 shows a comparison between processed aircraft movements and EUROCONTROL data (EUROCONTROL, 2018), in terms of both hourly distribution of flight events and aircraft fleet composition. In Sections 3.2–3.4, the results obtained for London Heathrow, Amsterdam Schiphol and Vienna-Schwechat are represented separately, while LDEN and GT maps for the other six airports are reported in Section 3.5. More space is devoted to Heathrow, Schiphol and Schwechat, since the official noise data available at those airports enable validation of the present predictions.

3.1. Analysis of air traffic

The number, type and characteristics of the flight events retrieved from FlightAware were compared with official air traffic data from EUROCONTROL’s DDR2 service (EUROCONTROL, 2018), where datasets of European daily historical air traffic are made available with a delay of 4–5 days. The M3 files of these datasets, resulting from flight plans enriched with radar data, are used to reconstruct the daily air traffic at the considered airports. However, DDR2 data report only ICAO aircraft type designators, and the 4-D (space and time) trajectories refer simply to ATC sectors, without any association with the airport runways. Therefore, EUROCONTROL data cannot be used as a substitute for flight tracker data, and only the aircraft types and the date and time of the flight events were considered for the comparison with the present air traffic predictions.

Fig. 8 shows the results of the comparison for the airports of Heathrow, Schiphol and Madrid-Barajas. At Heathrow Airport, the predicted air traffic figures agree very well with the historical data concerning type/number of events (+1.3% arrivals, −3.0% departures), their hourly distribution, and aircraft types. At Schiphol, the number of arrivals is predicted equally well (+1.3%), but the number of departures is underestimated by about 10%, and slightly larger maximum deviations are observed in the hourly

Fig. 8. Comparison of hourly distribution of flight events (left) and most common aircraft types (right) at Heathrow, Schiphol and Madrid-Barajas on 11 June 2018. FA represents the air traffic estimated from FlightAware web data, while EC refers to EUROCONTROL data.
distribution of the events and aircraft types. Finally, for Madrid-Barajas, much larger differences are reported, with about 23% fewer departures and 5% fewer arrivals. The analysis of these cases shows that the primary reason for the observed discrepancies is the difference in the number of flight events (especially departures). Multiple factors contribute to this disagreement:

1. **Absence of flight information**: some flights are not reported by the flight tracker, probably because the aircraft does not have an active ADS-B transponder or, for non-commercial flights, the aircraft owner has opted out of public flight tracking.

2. **Irretrievability of departures**: occasionally, a departed flight is listed correctly by the flight tracker, but the information cannot be accessed via API for unknown reasons. It was observed that up to 5% of daily departures were not retrievable at some airports.

3. **Duplication of flights**: during the live tracking of a flight, the flight number changes, leading to two (incomplete) separate flight histories for the same flight. About 1% of the flights turned out to be affected by this occurrence.

4. **Pre-processing of raw flight data**: a few flight events were lost as reported in Section 2.3.

A thorough analysis of the results shows that in most airports, independently of the targeted day, the comparison of estimated air traffic with official data results in deviations similar to those found at Heathrow (Vienna-Schwechat) or Schiphol (the majority of airports). Madrid-Barajas and, to a lesser extent, Naples represent significant exceptions, where factor (1) seems to be the main reason for the underestimation of flight events. In fact, the analysis of local air traffic shows that the missing events refer mostly to flights operated by certain private airlines.

### 3.2. Heathrow Airport

Heathrow Airport, located to the west of London, is one of the largest airports in the world, featuring two parallel east-west runways and serving more than 75 million passengers every year (Heathrow: Facts and figures, 2018). For 11 June 2018, the air traffic figures have been reported in the previous section, while the calculated ground track and \( L_{DEN} \) contour maps are shown in Fig. 9. The ground track map in Fig. 9(a) shows significant differences between departure and arrival paths. In particular, four holding stacks for approaches are identified, which correspond to the locations of Bovingdon, Lambourne, Biggin and Ockham. Furthermore, prevailing aircraft movements from west to east are observed (so-called easterly operations), which is explained by the 5-to-10-knot wind blowing all day from the north-east (aircraft usually take off and land into the wind). The \( L_{DEN} \) contour map in Fig. 9(b) exhibits a long and narrow footprint on the left-hand side, mainly generated by arrivals, and some lateral high-noise regions on the right, caused primarily by departing aircraft.

For the second targeted day, 13 June 2018, 666 departures and 690 arrivals were processed, which again compares very well with the 681 departures (−2.2%) and 681 arrivals (+1.3%) provided by EUROCONTROL. Apart from the early morning, a 10-to-15-knot wind came from the south-west, leading to the most typical management of air traffic at Heathrow, i.e., westerly operations. Indeed, the calculated ground track map in Fig. 10(a) is basically the reverse of the previous one except for the four holding stacks. Also noise contours in Fig. 10(b) appear almost mirrored with respect to those in Fig. 9(b).

For Heathrow Airport, an average daily noise contour map obtained with the ANCON model is available in ERCD report 1701 (Environmental Research and Consultancy Department, 2017) for the year 2016, in which a westerly-easterly modal split of 70%-30% was observed. The noise maps in Figs. 9(b) and 10(b) can be considered two paradigmatic examples of easterly and westerly operations, respectively, and hence it seems reasonable to compare their 30–70% blend with the ANCON average noise map.

---

**Fig. 9.** (a) Ground track and (b) \( L_{DEN} \) contour maps at Heathrow Airport (11 June 2018).
Therefore, the following weighted average of $L_{DEN}$ was computed at each receiver location:

$$L_{DEN} = 10 \log_{10} \left( 0.3 \cdot 10^{L_{DEN,13June}} + 0.7 \cdot 10^{L_{DEN,14June}} \right)$$  \hspace{1cm} (10)

and the resulting noise map is compared with the ANCON one in Fig. 11. The two sets of noise contours exhibit very similar shapes and small to moderate differences in the noise levels. In fact, ANCON levels are typically 1–3 dB(A) higher than the present predictions, reaching almost 5 dB(A) in a limited region to the south-west of the runways. This underestimation is caused by several factors, the most important of which is the uneven comparison between a blend of two single-day maps and a yearly average daily noise map. Additionally, the ANCON model is calibrated using noise measurements performed just at Heathrow, and ANCON flight profiles are based on operational radar data, which provide a more accurate description of aircraft 4-D trajectories. On the other hand, the ANCON results are two years older than the present ones, and the reduction in noise levels from 2016 to 2018 due to improved aircraft fleet and traffic management (see ERCD report (Environmental Research and Consultancy Department, 2017)) could be partially responsible for the lower values of predicted $L_{DEN}$.

3.3. Amsterdam Airport Schiphol

Amsterdam Airport Schiphol is the largest airport in the Netherlands, lying 9 km south-west of Amsterdam and accounting for more than 65 million passengers per year, with an average of 1,350 flights per day (Schiphol Amsterdam Airport, 2018). The airport
has six runways, five of which (18L/36R, 06/24, 09/27, 18C/36C, 18R/36L)\(^1\) usually accommodate commercial traffic, while the shortest one (04/22) is mainly reserved for general aviation. The runways and their designations are shown in Fig. 12.

For 11 June 2018, the air traffic reconstructed from flight tracker data and its comparison with EUROCONTROL data are reported in Section 3.1, whereas the calculated ground track and \(L_{DEN}\) contour maps are shown in Fig. 13. Looking at the central portion of Fig. 13(a), it is observed that most of the arriving aircraft landed from the south and south-west, while departures took place towards the north and north-east, according to the prevailing wind direction (from the north-east all day long). The retrieved aircraft positions closest to the airport led the pre-processing program to assign most of the arrivals to runways 06 and 36R, and the majority of departures to runways 36L and 36C. According to the ground track distribution, the noise map in Fig. 13(b) exhibits two long and narrow footprints due to approaches to the south and south-west of the airport, whereas wider footprints, usual for departing flights, are observed to the north of the two take-off runways.

Noise levels at Schiphol are measured in real time by monitoring system NOMOS (Casper NoiseLab, 2018), and daily historical data are made available to the public. In particular, maximum levels \(L_{A,max}\) are measured at 41 stations, and results are provided in form of daily indices \(NAT_{60}, NAT_{70},\) and \(NAT_{80},\) and frequency distributions of noise events with 2-dB(A) class interval. In order to compare the present noise predictions with NOMOS measurements, the noise computation has been carried out for 11 June at 15 receiver positions chosen among the 41 NOMOS stations. These positions, indicated in Fig. 12, have been selected as the best representative samples for the airport (disregarded stations are either very close to the selected ones or too far away from the airport).

Table 2 reports the comparison between computed and NOMOS \(NAT\) values at the 15 selected stations. It is observed that the deviation between computed and NOMOS data is strongly correlated to the location of the measurement station. In particular, the largest differences are found to the north of the airport, where departure events dominate, whereas a much better agreement is observed at the stations located to the south of it. This outcome was expected, because 80 departures were lost (see Section 3.1), and take-offs are difficult to model in terms of both flight profile type (multiple choices are possible, see Appendix A) and runway assignment (ADS-B data may not be available at the beginning of the flight, and the aircraft can turn suddenly just after lifting off). Furthermore, some measurement stations are placed on the rooftop of buildings, whereas the computed noise levels refer to receivers located near the ground.

A thorough analysis of the noise event distributions over \(L_{A,max}\) at the considered stations confirmed the sensitivity of the present predictions to the type of flight event (departure or arrival). As a representative example, Fig. 14 reports the frequency distributions of noise levels at station 92, located north of the runways, and station 40, located to the south of them. These histograms show that levels \(L_{A,max}\) are significantly underestimated (up to 6–8 dB(A)) in areas that are interested primarily by departures (station 92), whereas the predictions at station 40, mainly affected by noise from approaching aircraft, match the measured levels very well.

3.4. Vienna-Schwechat Airport

Vienna-Schwechat Airport, the largest airport of Austria, is an international hub that serves around 24 million passengers every year. It is located 18 km south-east of Vienna, and features two runways (16/34 and 11/29) that accommodated a daily average of 615 flights in 2017 (Viennaairport – Traffic Results – Flughafen Wien, 2018).

For this airport, the analysis of air traffic and noise levels has been conducted for Sunday, 10 June 2018 and Tuesday, 12 June 2018. For the first day, 357 departures and 353 arrivals were collected and processed, being in good agreement with the 374 departures (−4.5%) and 350 arrivals (+0.8%) listed by EUROCONTROL (EUROCONTROL, 2018). For 12 June, 349 departures and 368 arrivals were detected, resulting in a greater underestimation of the daily air traffic when compared to EUROCONTROL’s 375 departures (−6.9%) and 380 arrivals (−3.1%).

The calculated maps of ground tracks and noise level \(L_{DEN}\) for the two days are shown in Figs. 15 and 16, respectively. According to weather reports, on 10 June both wind direction and speed changed continuously during the morning, stabilising into a 5-to-8-knot south-west wind in late afternoon. Instead, on 12 June a strong morning wind (10–17 kt) from the west was replaced in the afternoon by moderate gusts (up to 10 kt) coming alternately from the north-east and the south-west. Despite markedly different weather conditions, the comparison of the ground tracks in Figs. 15(a) and 16(a) indicates only minor variations in the management of the air traffic, the prevailing flight events being departures from runway 29 and arrivals on runways 16 and 34 on both days. Consistently with the aircraft movements, the \(L_{DEN}\) contour maps in Figs. 15(b) and 16(b) show comparable shapes and noise levels. Extended narrow footprints, mainly due to arrivals, can be observed in the direction of runway 16/34 and to the south-east of the airport in the direction of runway 11/29, whereas departures are mainly responsible for the high noise levels on the left-hand side of the maps. The similarity between the two noise contour sets is probably explained by the presence of the city of Vienna a few kilometres north-west of the airport. In fact, aircraft movements seem to be managed with the purpose of avoiding air traffic over the city, thus limiting the possible approach routes.

Similarly to Schiphol, Vienna-Schwechat features an air traffic and noise monitoring system, which provides the public, via website Flugspuren (Austro Control), with air traffic statistics, plots of aircraft trajectories, and cumulative noise levels at 15 monitoring stations. Whereas the graphical form of aircraft trajectories is unsuitable for a comparison with the present GT maps, air traffic

\(^1\)The name of a runway is composed of a pair of two-digit numbers (e.g., 09/27) that represent the angles in degrees, divided by 10 and measured clockwise, between the runway and the north direction. Letters L (left), C (centre), R (right) that occasionally follow the numbers denote the mutual positions of parallel runways. Designating the runway with either of the two numbers allows specifying the direction travelled by the aircraft (e.g., 09 if the aircraft moves from west to east, 27 otherwise).
and noise figures can be easily compared with the present predictions. For both departures and arrivals, Flugspuren provides daily runway splits, which are compared in Table 3 with the present runway assignments for the two days. Modelled and Flugspuren (FS) splits show similar trends, but the events on runway 11 and the departures on runway 16 are somewhat overestimated, while the usage of the other runways, primarily 29, is correspondingly underestimated.

Concerning noise, the same operations described for Schiphol have been performed to compute noise levels at the 15 monitoring stations shown in Fig. 17. However, in this case only monthly average $L_{eq,\text{day}}$ and $L_{eq,\text{night}}$ are available, and the 16-hour daytime lasts from 6:00 to 22:00. After modifying the computer code to account for the new time slots, $L_{eq,\text{day}}$ and $L_{eq,\text{night}}$ have been computed and compared with the monthly averages, as shown in Table 4.

Although monthly averages prevent a direct comparison with predicted levels, the results in Table 4 form a basis for conducting at least a qualitative analysis. The table shows similar variations of daily and monthly average levels with monitoring station, especially for $L_{eq,\text{day}}$, and the higher the average noise level, the better the agreement. In fact, the largest differences are observed at low average levels, with maximum deviations for night levels at stations 14 and 15. Two factors are mainly responsible for these differences, namely the sound threshold of the microphones used in the monitoring stations, and the effect of a few flight events with poor flight tracking information. In fact, microphones used at Schwechat have a 27-dB(A) lower threshold (Brüel and Kjær) that removes the sound energy contribution of quiet noise events, which nevertheless significantly affects low average noise levels.

![Fig. 12. Runways at Schiphol Airport (thick solid segments) and locations of selected NOMOS monitoring stations (cross markers).](image1)

![Fig. 13. (a) Ground track and (b) $LDEN$ contour maps at Schiphol Airport (11 June 2018).](image2)
Moreover, in some cases few points are available for the construction of a reliable flight trajectory due to a lack of ADS-B data, and wrongly reconstructed overflights have a greater impact on the monitoring stations where the measured noise levels are normally low.

Table 2
Computed and measured (NOMOS) NAT values at Schiphol on 11 June 2018.

<table>
<thead>
<tr>
<th>Station</th>
<th>$NAT_{60}$</th>
<th>$NAT_{70}$</th>
<th>$NAT_{80}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Model</td>
<td>NOMOS</td>
<td>Model</td>
</tr>
<tr>
<td>1</td>
<td>318</td>
<td>154</td>
<td>0</td>
</tr>
<tr>
<td>7</td>
<td>37</td>
<td>61</td>
<td>1</td>
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<tr>
<td>10</td>
<td>238</td>
<td>257</td>
<td>230</td>
</tr>
<tr>
<td>13</td>
<td>1</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>14</td>
<td>482</td>
<td>468</td>
<td>43</td>
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<tr>
<td>17</td>
<td>50</td>
<td>29</td>
<td>3</td>
</tr>
<tr>
<td>19</td>
<td>236</td>
<td>358</td>
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</tr>
<tr>
<td>29</td>
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</tr>
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<td>34</td>
<td>103</td>
<td>106</td>
<td>2</td>
</tr>
<tr>
<td>40</td>
<td>246</td>
<td>230</td>
<td>228</td>
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<tr>
<td>45</td>
<td>58</td>
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<td>0</td>
</tr>
<tr>
<td>92</td>
<td>249</td>
<td>221</td>
<td>198</td>
</tr>
</tbody>
</table>

Fig. 14. Comparison between computed and measured frequency distributions of noise events over 2-dB(A)-wide $La_{max}$ classes for stations 92 (left) and 40 (right). Levels $La_{max}$ below 60 dB(A) are not provided by NOMOS.

Fig. 15. (a) Ground track and (b) $L_{DEN}$ contour maps at Vienna Airport (10 June 2018).
3.5. Other airports

The assessed flight events at each of the other six airports are reported in Table 5, together with the respective wind conditions. For all airports, the targeted day was 11 June 2018.

Calculated ground track maps and $L_{DEN}$ noise contour maps for these airports are shown in Figs. 18–23. All ground track and noise

Table 3
Comparison between modelled and actual (FS) runway splits at Vienna-Schwechat.

<table>
<thead>
<tr>
<th>Runway</th>
<th>Event</th>
<th>10 June</th>
<th>12 June</th>
<th>10 June</th>
<th>12 June</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Model</td>
<td>FS</td>
<td>Model</td>
<td>FS</td>
</tr>
<tr>
<td>11</td>
<td>D</td>
<td>4%</td>
<td>0%</td>
<td>7%</td>
<td>4%</td>
</tr>
<tr>
<td></td>
<td>A</td>
<td>5%</td>
<td>3%</td>
<td>3%</td>
<td>0%</td>
</tr>
<tr>
<td>16</td>
<td>D</td>
<td>14%</td>
<td>7%</td>
<td>7%</td>
<td>0%</td>
</tr>
<tr>
<td></td>
<td>A</td>
<td>44%</td>
<td>49%</td>
<td>20%</td>
<td>20%</td>
</tr>
<tr>
<td>29</td>
<td>D</td>
<td>70%</td>
<td>85%</td>
<td>60%</td>
<td>70%</td>
</tr>
<tr>
<td></td>
<td>A</td>
<td>23%</td>
<td>22%</td>
<td>9%</td>
<td>6%</td>
</tr>
<tr>
<td>34</td>
<td>D</td>
<td>12%</td>
<td>8%</td>
<td>26%</td>
<td>25%</td>
</tr>
<tr>
<td></td>
<td>A</td>
<td>28%</td>
<td>25%</td>
<td>68%</td>
<td>73%</td>
</tr>
</tbody>
</table>

Fig. 17. Locations of noise monitoring stations around Vienna-Schwechat.

3.5. Other airports

The assessed flight events at each of the other six airports are reported in Table 5, together with the respective wind conditions. For all airports, the targeted day was 11 June 2018.

Calculated ground track maps and $L_{DEN}$ noise contour maps for these airports are shown in Figs. 18–23. All ground track and noise
maps exhibit a marked directionality, which depends on the number and orientation of the runways, and the wind direction on the selected day. As done for Heathrow, Schiphol, and Schwechat, similar observations can be made on the air traffic management at each of the other six airports, with special reference to the need for limiting departure and arrival routes over highly populated areas.

The results presented here refer to European airports of very different sizes, and they are only a few examples of the applicability of the proposed approach to the prediction of aircraft noise around airports. In fact, the present tool can be applied without restrictions to any airport in the world if sufficient web data on flight histories, aircraft models, and runway layouts are available.

Table 4
Monthly average $L_{Aeq,day}$ and $L_{Aeq,night}$ at Vienna-Schwechat compared with daily predictions for 10 June and 12 June.

<table>
<thead>
<tr>
<th>Station</th>
<th>$L_{Aeq,day}$ [dB(A)]</th>
<th>$L_{Aeq,night}$ [dB(A)]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>June avg. 10/6</td>
<td>12/6</td>
</tr>
<tr>
<td>1</td>
<td>45.7</td>
<td>51.6</td>
</tr>
<tr>
<td>2</td>
<td>50.8</td>
<td>55.2</td>
</tr>
<tr>
<td>3</td>
<td>30.7</td>
<td>43.1</td>
</tr>
<tr>
<td>4</td>
<td>52.9</td>
<td>57.2</td>
</tr>
<tr>
<td>5</td>
<td>54.6</td>
<td>55.7</td>
</tr>
<tr>
<td>6</td>
<td>54.4</td>
<td>55.8</td>
</tr>
<tr>
<td>7</td>
<td>64.5</td>
<td>58.3</td>
</tr>
<tr>
<td>8</td>
<td>30.9</td>
<td>44.2</td>
</tr>
<tr>
<td>9</td>
<td>55.1</td>
<td>51.2</td>
</tr>
<tr>
<td>10</td>
<td>53.4</td>
<td>52.7</td>
</tr>
<tr>
<td>11</td>
<td>50.0</td>
<td>47.9</td>
</tr>
<tr>
<td>12</td>
<td>46.1</td>
<td>42.5</td>
</tr>
<tr>
<td>13</td>
<td>41.4</td>
<td>44.1</td>
</tr>
<tr>
<td>14</td>
<td>42.1</td>
<td>41.8</td>
</tr>
<tr>
<td>15</td>
<td>47.7</td>
<td>45.0</td>
</tr>
</tbody>
</table>

Table 5
Flight events at six European airports (FA: present predictions, EC: EUROCONTROL data).

<table>
<thead>
<tr>
<th>Airport</th>
<th>Wind direction</th>
<th>Wind speed</th>
<th>Departures</th>
<th>Arrivals</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>FA</td>
<td>EC</td>
<td>FA</td>
<td>EC</td>
</tr>
<tr>
<td>Frankfurt</td>
<td>NNE, NE</td>
<td>8–12 kt</td>
<td>639</td>
<td>696</td>
</tr>
<tr>
<td>Madrid – Barajas</td>
<td>Variable, mostly SW</td>
<td>3–10 kt</td>
<td>468</td>
<td>612</td>
</tr>
<tr>
<td>Paris – CDG</td>
<td>NNE, NE</td>
<td>5–11 kt</td>
<td>621</td>
<td>699</td>
</tr>
<tr>
<td>Rome Fiumicino</td>
<td>SE through SW</td>
<td>4–14 kt</td>
<td>438</td>
<td>473</td>
</tr>
<tr>
<td>Trieste</td>
<td>Variable, mostly SW</td>
<td>2–10 kt</td>
<td>14</td>
<td>16</td>
</tr>
<tr>
<td>Naples International</td>
<td>Variable, mostly S</td>
<td>2–9 kt</td>
<td>105</td>
<td>134</td>
</tr>
</tbody>
</table>

Fig. 18. (a) Ground track and (b) $L_{DEN}$ contour maps at Frankfurt Airport (11 June 2018).
4. Conclusions

A novel approach to the prediction of airport noise has been presented, which is based on the retrieval and exploitation of large amounts of data on civil air traffic and aircraft fleets currently available on the web. A new methodology is introduced for the identification of flight events at an airport (departures and arrivals) and the reconstruction of aircraft flight paths according to the ECAC procedure. All flight events at the airport are processed to compute single event noise levels and cumulative noise metrics at selected positions on the ground by means of the ECAC noise model, and daily noise contours in the airport area are finally computed.

A total of 10,752 flight events were collected in nine European airports of different sizes. About 99% of these events were successfully processed and employed for the computation of $L_{DEN}$ contour maps using a grid of 11,881 sound receivers placed on a 2,440 km$^2$ airport area.

The predicted air traffic agrees well with official EUROCONTROL figures in seven of the nine airports studied, whereas an underestimation of daily events, especially departures, is observed at Madrid-Barajas and Naples airports. In all cases, the predicted noise footprints appear reasonable and consistent with the ground tracks.

The availability of historical data at Heathrow, Schiphol and Vienna-Schwechat airports has allowed a partial validation of the present approach. For Heathrow, a satisfying agreement is found between a blend of two single-day $L_{DEN}$ contour maps and an official yearly average daily noise map. The comparison of computed $NAT$ values and frequency distributions of $L_{Amax}$ with data acquired at
15 monitoring stations around Schiphol shows larger deviations at the positions mostly affected by departing flights. For Vienna-Schwechat, an acceptable agreement is obtained between predicted and official runway splits on two different days, while computed values of $L_{Aeq\,\text{day}}$ and $L_{Aeq\,\text{night}}$ at 15 stations compare well with monthly average levels, except for the cases when such levels are very low.

The application of the present methodology to the prediction of air traffic and noise footprints at the considered airports results in accurate reconstructions of arrival events and noise levels in areas where their effects are prevalent. On the contrary, incomplete flight tracker data on departing flights lead to less reliable runway assignment, ground track and flight path generation, and hence noise level prediction.

When compared to arrival events, departures need much more data to be fully characterised because of the larger variability of aircraft trajectories and procedural steps. Therefore, lack of data due to inactive or absent ADS-B transponders aboard a departing aircraft makes the reconstruction of the flight event much more difficult, if not impossible. However, a larger availability of flight data is expected in the near future, mainly due to the mandatory installation of ADS-B transponders by 2020 in accordance with EU regulations and to the increasing development of the flight tracker websites. These occurrences should make the application of the proposed methodology more and more effective, thus increasing the value of the present approach.

As far as possible improvements of the present procedure are concerned, the reconstruction of the flight profile for departures and the runway assignment could be made more reliable by using flight tracking data to supplement the synthesis of the flight profile and

Fig. 21. (a) Ground track and (b) $L_{DEN}$ contour maps at Rome Airport (11 June 2018).

Fig. 22. (a) Ground track and (b) $L_{DEN}$ contour maps at Trieste Airport (11 June 2018).
by performing a statistical analysis of well-defined events to adjust the aircraft trajectories close to the runways. Furthermore, more accurate noise predictions could be obtained by considering the effects of the orography of airport areas and the actual atmospheric conditions (wind speed and direction, temperature, pressure, etc.) during each flight event. Also in this regard, web data retrieval appears to be a mandatory and feasible starting point.

The methodology presented here is capable of quantifying aircraft noise from real-world air traffic operations, joining and re-interpreting information from multiple web sources, such as flight trackers and aircraft model, performance and noise databases. The availability of large amounts of flight data from the web and the general applicability of the present approach may allow aviation operators to investigate also future scenarios at airports of any size, taking into account the changes in aircraft fleet composition and air traffic. The impact of a different aircraft fleet on airport noise could be estimated by substituting old aircraft with current best-in-class models, while new-generation aircraft might be modelled by reasonably altering the properties of current ANP proxies, in anticipation of official certification test data. Concerning air traffic, the detrimental effects of additional aircraft movements could be assessed by assigning more flight events to existing routes. Thus, policy- and decision-makers are provided with a powerful tool for evaluating the consequences of different strategic choices on air transport at local, national, and global levels.

Acknowledgements

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Declarations of interest

None.

Appendix A. Synthesis of the flight profile from procedural steps

The construction of a flight profile results from the application of a sorted sequence of a limited number of ANP procedural steps (European Civil Aviation Conference, 2016b). At the starting point (1) and endpoint (2) of each flight profile segment the following parameters are defined:

- calibrated airspeed $V_C$ (the airspeed measured by a probe on the aircraft);
- altitude $H$ (= height $z +$ ARP elevation);
- true airspeed $V_T = V_C/\sqrt{\sigma}$ (accounting for air density ratio $\sigma = \rho(H)/\rho(0)$);
- groundspeed $V = V_T \cos \gamma - w$ ($\gamma$ is the climb/descent angle, $w$ is the wind speed);
- corrected net engine thrust $F/\delta$ (accounting for air pressure ratio $\delta = p(H)/p(0)$);
- ground coordinate $s$.

Although procedural steps are different for each proxy, they always fall into the categories listed in Table A1. A single flight profile may include multiple steps belonging to the same ANP category.

For each procedural step, the six parameters listed above are known at the starting point of the profile segment, and the values of

Fig. 23. (a) Ground track and (b) LDEN contour maps at Naples Airport (11 June 2018).
targets and known parameters in Table A1 are used to compute the parameters at the segment endpoint. The calculation procedure consists in the solution of flight mechanics equations, which often include aerodynamic and engine parameters provided in the ANP database. For instance, the corrected net thrust of one engine, \( F_n \), in a descent step is computed by means of the following force balance equation:

\[
\frac{F_n}{\delta} = W \frac{R \cos \gamma + \sin \gamma + a/g}{\delta \cdot N_{\text{eng}}} \tag{A.1}
\]

where \( W \) is the aircraft weight, \( R \) is the drag-to-lift ratio, provided by ANP as a function of the flap setting, \( \gamma < 0 \) is the known descent angle, \( N_{\text{eng}} \) is the number of engines, and \( g \) is the gravitational acceleration. Deceleration \( a \) in Eq. (A.1) is calculated using the kinematic equation:

\[
a = \frac{(V_1/\cos \gamma)^2 - (V_2/\cos \gamma)^2}{2 \Delta s/\cos \gamma} \tag{A.2}
\]

where groundspeeds \( V_1 \) and \( V_2 \) are derived from the respective calibrated airspeeds, and ground step length \( \Delta s = |s_2 - s_1| \) is easily computed from known heights \( z_1 \) and \( z_2 \):

\[
\Delta s = \frac{z_2 - z_1}{\tan \gamma} \tag{A.3}
\]

Eqs. (A.1)–(A.3) complete the computation of the procedural step and provide the starting values of the parameters for the following step. Similar calculations are performed for departure procedures, an example of which is provided in the text (Fig. 6).

The ECAC procedure for the synthesis of the whole flight profile is based on the following assumptions:

1. the maximum profile heights are 10,000 ft for departures and 6000 ft for arrivals;
2. arrival procedures end when the aircraft reaches a calibrated airspeed of 30 kt;
3. the acceleration (or deceleration) is constant inside each procedural step.

The departure procedures described by ECAC allow accounting for thrust reduction during take-off and climb steps, which requires the knowledge of actual aircraft weight, detailed runway characteristics, and airline operators’ practices. As this information is not available here, thrust reduction is not considered in the present work.

For most proxies the ANP database lists multiple “default” departure profiles depending on the take-off weights, and a single “default” approach profile. In some cases, two additional non-default departure profiles (“ICAO_A” and “ICAO_B”) are provided, which include some different procedures aimed at reducing noise emissions in specific areas. Such profiles have not been considered in the present work, since their application requires a thorough knowledge of the regulations enforced at each airport. Finally, for a few proxies, profiles based on procedural steps are not available, and they are replaced by fixed-point profiles, the parameters of which are prescribed at fixed ground coordinates and no mechanical calculations are required.

### Appendix B. Procedure for the construction of the flight path

According to the ECAC procedure, the first step of the flight path construction is the sub-segmentation of the flight profile segments to enable more accurate calculation of single event noise levels (European Civil Aviation Conference, 2016b). This operation is carried out by imposing a maximum change of the groundspeed, \( \Delta V_{\text{max}} = 20 \text{ kt} \), inside each sub-segment. At the intermediate points, the aircraft height is obtained by linear interpolation along the ground coordinate, whereas groundspeed and corrected net thrust are computed by quadratic interpolation.

At the ends of each flight profile sub-segment, the following parameters are known:

- ground coordinates \( s_1, s_2 \);
- aircraft heights \( z_1, z_2 \);
- groundspeeds \( V_1, V_2 \);
- corrected net thrusts of one engine \( P_1, P_2 \) (\( P = F_n/\delta \) is the “power” for NPD data).
On the other hand, at the ends of each ground track segment the known parameters are:

- ground coordinates \( s_1, s_2 \) (different, in general, from \( s_1, s_2 \));
- Cartesian coordinates \( (x_1, y_1), (x_2, y_2) \);
- turn radius \( r \).

The flight path is composed of a number of segments, the end-points of which result from merging the end-points of the flight profile sub-segments and those of the GT segments. To do this, the first ones need to be assigned Cartesian coordinates recovered from the GT, whereas the second ones need to be assigned the correct values of the operational parameters from the flight profile. Cartesian coordinates \( (x_i, y_i) \) of a sub-segment endpoint having ground coordinate \( s_j \) are computed by interpolating coordinates \( (x_1, y_1), (x_2, y_2) \) of the GT segment for which \( s_1 < s_j < s_2 \):

\[
\begin{align*}
x_j &= x_1 + f(x_2 - x_1) \\
y_j &= y_1 + f(y_2 - y_1)
\end{align*}
\]  
\( \text{(B.1)} \)

where \( f = (s_j - s_1)/(s_2 - s_1) \) is the interpolation factor.

A similar operation is performed to associate parameters \( z_\ell, V_\ell, P_\ell \) to a GT point having ground coordinate \( s_\ell \). After identifying the end-points of the profile sub-segment such that \( s_1 < s_\ell < s_2 \), the same interpolations performed for the flight profile sub-segmentation are applied using interpolation factor \( f' = (s_\ell - s_1)/(s_2 - s_1) \).

The last action is the computation of the bank angle at each flight path point by means of the equation:

\[
\varepsilon = \tan^{-1}\left(\frac{2.85 - V_z^2}{g/r}\right)
\]  
\( \text{(B.3)} \)

where coefficient 2.85 is the conversion factor from \text{kt}^2 to \text{ft/s}^2, and \( r = r' \) is the turn radius of the ground track. Bank angle \( \varepsilon \) is also assigned a sign according to the turning direction (positive for left turns, negative otherwise).

References

- Environmental Research and Consultancy Department, 2017. ERCD REPORT 1701. Civil Aviation Authority.


