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AN OPEN-SOURCE TOOL FOR AIRCRAFT NOISE MODELING IN THE CONTEXT OF SPAIN'S GLOBAL NOISE ASSESSMENT (UNDER DEVELOPMENT)

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ABSTRACT

As part of the global noise assessment initiative in Spain, through a National Noise Strategy, which aims to address the lack of a comprehensive understanding of noise pollution, we present progress in the development of an open-source Python tool for modeling and analyzing aircraft noise. Currently, strategic studies are limited to airports with more than 50,000 annual operations, which excludes a significant number of relevant aeronautical infrastructures. This limitation is insufficient to fully understand the global impact of aviation noise, especially in rural or less densely populated areas. Our tool implements the equations of ECAC Document 29, which will allow the calculation of key metrics, SEL and LAmax, on a large scale and on a periodic basis. Furthermore, it will facilitate the use of data from big data platforms such as OpenSky Network. Its modular and scalable design can allow for integration with other open-source software, expanding its functionality and adaptability to different scenarios, or for use on its own. With this initiative, we aim to address the current gaps in the strategic analysis of aircraft noise, promoting the development of more inclusive and accessible mitigation policies for the entire Spanish territory.

Keywords: *aircraft noise, open-source modeling, ECAC Doc 29, noise assessment, strategic noise mapping*

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1. INTRODUCTION

The challenges posed by aircraft noise have become a major public concern, recognized for their impact on both population health and environmental quality [1]. Long-term exposure to aircraft noise has been linked to various adverse effects, such as increased stress levels, and sleep disturbances [2, 3]. These impacts extend beyond simple annoyance, as demonstrated by systematic reviews emphasizing the correlation between noise exposure and psychological disorders such as anxiety or depression [2, 4].

Despite growing evidence of the negative implications of aircraft noise, current strategic assessments conducted in Spain, in accordance with the Environmental Noise Directive, appear to be insufficient. They focus primarily on large airports handling more than 50,000 operations per year, leaving a considerable number of smaller aviation infrastructures unaccounted for in the assessments [5]. Consequently, this omission limits comprehensive noise assessment efforts, resulting in a fragmented understanding of the broader implications of aircraft noise in different environments [3, 6]. A more comprehensive and inclusive assessment is needed to implement effective management and mitigation strategies, such as a National Noise Strategy, supported by reliable and accessible tools for environmental noise assessment.

The increasing availability of innovative technologies and open-source tools can significantly improve noise modeling initiatives [7]. An effective assessment tool not only provides accurate data on noise levels but also acts as a platform for public engagement, helping to bridge the gap between affected communities and regulators [2, 8].

2. OBJECTIVES

The main objective of this study is to develop an open-source software tool for general-scale aircraft noise calculation, applicable at a national level, using flight trajectory data from various sources. To achieve this, two specific tools are being developed:

- **Flight Path Tool:** This tool extracts the required parameters from real flight data based on ECAC Doc 29 (ECAC29), Volume 2, Chapter 3: *Description of the Flight Path.*
- **Noise Calculation Tool:** This tool implements:
  - Chapter 4: *Noise Calculation for a Single Event.*
  - Chapter 5: *Calculation of Cumulative Levels.*
  - Chapter 6: *Calculation of Noise Contours.*

Once these modules are developed, the ultimate goal is to enable large-scale noise calculations by processing raw flight data, ensuring efficient and scalable analysis of aircraft noise impacts in a periodically updatable assessment.

3. MAIN REFERENCE WORKS

We highlight some of the works we consider most relevant related to the implementation of the ECAC29 [9] calculation model or other aeronautical noise calculation models in software, highlighting their contributions to understanding and mitigating aircraft noise. It is worth noting that the first [10] and second [11] works are related to a Matlab development of the ECAC calculation model. The first one code is available in the GitHub repository [1] .

The study by Casado, J., et al. (2023) [10] investigates missed approach maneuvers as a method to reduce noise and pollution associated with aircraft operations. By analyzing the implications of aircraft refueling strategies, the authors offer insights into practical approaches to minimizing the environmental impact of aviation activities, providing valuable data for regulatory measures and future modeling initiatives. The calculation tool is software developed by the authors.

The study by Zepeda Núñez, P.P.J. (2021) [11] focuses on the definition of a simplified aircraft noise model to study the impact of noise directivity patterns on a trajectory optimization tool called NOICE. This study underlines the importance of incorporating noise directivity into modeling to achieve more accurate assessments and effective noise mitigation strategies.

Meister, J., et al. (2021) [12] conducts a systematic comparison of different aircraft noise calculation software, providing critical assessments based on real-flight data. By highlighting discrepancies in noise predictions, it lays the groundwork for improving modeling accuracy and regulatory compliance.

Pretto, M. et al. (2020) [13] uses web data to predict noise emissions based on the ECAC Doc.29 model, demonstrating an innovative methodology that combines real-time data collection and predictive analytics to better inform noise management practices at airports.

Zellmann, A. et al. (2018) [14] presents an aircraft noise emission model that integrates detailed aircraft flight parameters into the noise calculation process. It serves to improve the predictive capability of noise emissions, representing a significant advancement in the modeling landscape.

Arntzen, K., et al. (2012) [15] explores the effects of varying weather conditions on noise contour predictions using the ECAC Doc. 29 model, highlighting important aspects of environmental influences on noise dispersion in urban environments.

These references, among many others, highlight the ongoing efforts to refine and expand noise modeling practices in the aviation sector, with particular attention to how various methodologies assess the environmental impact of aviation noise. They also emphasize the importance of applying crowdsourced data to modeling and its potential for studying aircraft noise.

4. METODOLOGY

The methodology applied in this work can be summarized in the selection of the programming language, the adaptation of the ECAC 29 prescriptions in the tools, and in the validation systems that are being applied.

4.1 Selected Programming Language

Although it is common for other projects to use MATLAB as the programming language for scientific tools [10], in this case, Python has been selected. Python is widely used in the scientific field due to its simplicity, readability, and extensive ecosystem of libraries that facilitate robust tool development [16]. Its clear syntax allows for easy code maintenance and debugging, which is crucial for scientific projects requiring verification and reproducibility [17]. Additionally, Python's large community provides

[1] https://github.com/GRCDEV/ANCM

access to numerous specialized libraries for data processing, mathematical computations, and geospatial analysis [18]. Its ability to seamlessly integrate various modules and file formats, such as CSV and JSON, makes it highly efficient for handling diverse datasets [19]. Moreover, its widespread adoption in research fosters collaboration and validation of methodologies [18].

Several key libraries, used in our code, enhance Python's capabilities in scientific applications. The **csv** library is used for tabular data processing, while the **os** library enables interaction with the operating system [20]. The **math** library provides essential mathematical functions, and **pandas** supports structured data analysis. For handling geospatial data, the **json** library is used for configuration files, and **shapely** enables geometric operations [21].

4.2 Flight Path Tool Implementation

Since the aim is to implement a segmentation tool that transforms massive flight data into segments compatible with the ECAC Doc. 29 model, no attempt has been made to emulate segmentation from the tables provided in ECAC29 Volume 3. Instead, work has been done on a tool that, by applying Chapter 3 of Volume 2 of ECAC Doc. 29, allows segmentation to be obtained from such massive data, for example, the OpenSky [2] Network [22].

Two modules have been depeloped at the moment. The first module prepares trajectory data from flight data sources, identifying distinct flight paths, ensuring chronological consistency, and computing distances between consecutive aircraft positions. Distance calculation between two geographical points (latitude and longitude) employs the Haversine Formula [23].

The second module segments the previously prepared trajectories strictly according to the guidance in ECAC Doc.29 (Section 3.6). It divides each flight trajectory into contiguous straight segments, performing linear interpolation of critical parameters such as height, velocity, and acoustic power, as explicitly indicated by the ECAC Equation 3.2a (Eqn. 1):

$$X(f) = X_{start} + f \cdot (X_{end} - X_{start}) \tag{1}$$

where $X(f)$ represents interpolated parameters (such as altitude, velocity, or power setting), and f is the fraction along the segment (0 at the beginning and 1 at the end).

Moreover, the segmentation procedure complies with ECAC guidelines for subdividing trajectory segments based on significant velocity changes. If the velocity difference between two consecutive points exceeds 10 m/s, the segment is subdivided according to the ECAC29 Equation 3.5 (Eqn. 2):

$$n_{seg} = \min\left(\left\lfloor 1 + \frac{\Delta V}{10}\right\rfloor, 5\right) \tag{2}$$

where ΔV is the absolute velocity difference between consecutive points (m/s), and n_{seg} is the resulting number of subsegments (up to a maximum of 5).

Additionally, vertical adjustments related to terrain elevation are applied in line with the ECAC methodology (section 3.3.4). The adjusted aircraft height relative to terrain or observer elevation is given by Equation 3:

$$z' = z - z_o \tag{3}$$

where z is the aircraft altitude, and z_o is the terrain (or observer) elevation.

Through this implementation, the Python code converts raw flight data into properly segmented flight paths in accordance with the ECAC Doc.29 Volume 2 (Section 3), ensuring accurate inputs for subsequent acoustic modeling procedures.

4.3 Noise Calculation Tool Implementation

The noise calculation tool implementation follows the methodology outlined in ECAC Doc 29 Volume 2 , Chapter 4, specifically focusing on the calculation of the segment-level noise metrics $L_{max,seg}$ and LE_{seg} (Sound Exposure Level).

The code structure is organized into distinct modules, each containing several scripts that, in summary, perform the following operations:

- **Input Data Module**: Responsible for loading aircraft performance and noise data from the ANP database, runway, and receptor information.
- **Geometric Calculations Module**: Calculates geometric parameters essential for determining distances, angles, and projection points.
- **Noise Calculation Module**: Computes the event noise levels per flight segment, implementing the equations described by ECAC.

The core of the noise calculation is based on the methodology described in ECAC Doc 29, particularly focusing on Equations (4-8a) and (4-8b):

[2] https://opensky-network.org/datasets/states/.

ECAC29 Equation (4-8a) defines the maximum level of noise for a single flight segment ($L_{max,seg}$) as:

$$L_{max,seg} = L_{max}(P,d) + \Delta I(\phi) - \Lambda(\beta,\ell) \quad (4)$$

Equation (4-8b) describes the sound exposure level for a segment ($L_{E,seg}$):

$$L_{E,seg} = L_E^{\infty}(P,d) + \Delta V + \Delta I(\phi) - \Lambda(\beta,\ell) + \Delta F \quad (5)$$

In the Python implementation, these equations are computed through several intermediate steps, structured as follows:

4.3.1 Baseline Noise Levels from NPD Data

First, the baseline event noise levels, $L_{max}(P,d)$ and $L_E^{\infty}(P,d)$, are interpolated from Noise-Power-Distance (NPD) tables, based on the corrected net thrust (power setting) and the slant distance (d) between the receptor and the flight segment midpoint.

4.3.2 Corrections

Duration Correction (ΔV): Implemented exclusively for sound exposure levels (SEL). This correction adjusts exposure based on the difference between actual segment duration and reference duration as provided by the NPD data:

$$\Delta V = 10 \log_{10}\left(\frac{V_{ref}}{V_{seg}}\right) \quad (6)$$

Engine Installation Correction:The engine installation correction ($\Delta I(\phi)$), which accounts for lateral directivity effects, is computed based on the depression angle (ϕ). This angle is calculated geometrically as the difference between elevation angle (β) and bank angle (ϵ).

Depending on the engine installation type defined for each aircraft (*'Fuselage'*, *'Wing'*, or *'Prop'*), specific empirical coefficients (as recommended by ECAC guidelines) are applied:

- For *'Fuselage'* installation:
  - $a = 0.1225, b = 0.329, c = 1$
- For *'Wing'* installation:
  - $a = 0.0039, b = 0.062, c = 0.8766$
- For *'Prop'* installation, no correction is applied:
  - $\Delta I(\phi) = 0$

Thus, the correction term $\Delta I(\phi)$ is calculated following the Equation 7 implemented in the Python code:

$$\Delta I(\phi) = 10 \cdot \log_{10}\left(\frac{\left(a \cdot \cos^2(\phi) + \sin^2(\phi)\right)^b}{c}\right) \quad (7)$$

Lateral Attenuation Calculation: The lateral attenuation, $\Lambda(\beta,\ell)$, is calculated following ECAC procedures, considering the elevation angle (β) and lateral distance (ℓ), applying empirical relationships provided in Section 4.5.4 and Equation 4-18 of ECAC and ECAC29 (Equation 8):

$$\Lambda(\beta,\ell) = \Gamma(\ell) \cdot \Lambda(\beta) \quad (8)$$

where $\Gamma(\ell)$ is a distance factor and $\Lambda(\beta)$ is long-range air-to-ground lateral attenuation calculated according to ECAC29 Equations 4-19 (a-d).

Finite Segment Correction (ΔF): The noise calculation for a single flight segment requires determining the fraction of sound energy contributed by each segment. In the implemented Python code, this fraction is computed for both SEL and L_{Amax} following ECAC Doc 29, using Appendix E equations, as well as the special cases defined by equations 4-20 and 4-21(a-b) for specific observer-segment positions.

In our the Python module, these calculations are performed sequentially. The structure of the Python code directly mirrors the ECAC methodology:

1. Calculate geometric parameters (β, ϕ, distances, etc.).
2. Extract NPD values and apply interpolations for baseline noise levels $L_{max}(P,d)$ and $L_E^{\infty}(P,d)$.
3. Apply corrections sequentially (engine installation, lateral attenuation, duration, and finite segment correction).

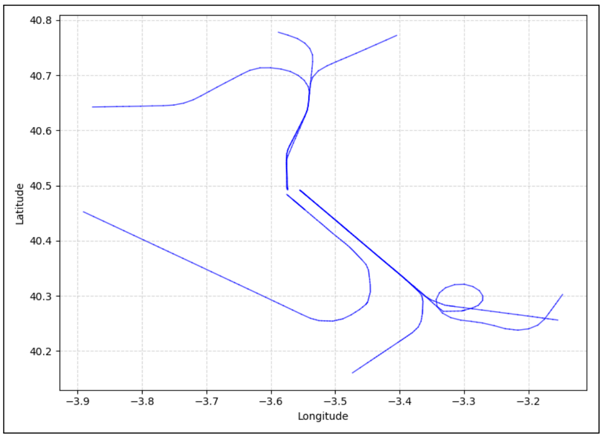
Thus, the Python implementation aims to closely adhere to the ECAC guidelines, to ensure that the calculations for $L_{max,seg}$ and $L_{E,seg}$ accurately reflect the intended methodology.

5. RESULT AND DISCUSSION

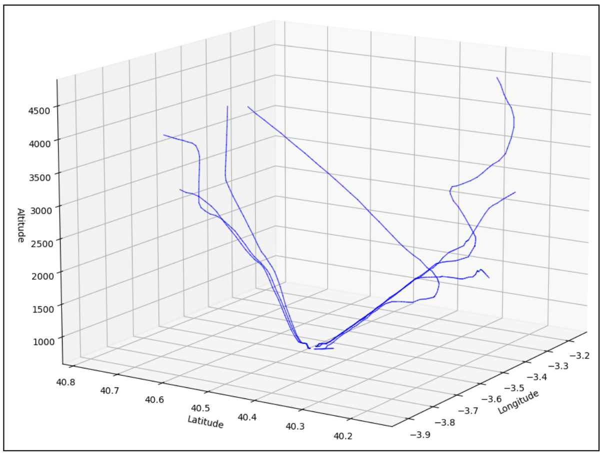
Below are the results obtained up to the time of writing this paper, highlighting that we are still in the process of developing and fine-tuning the tools described.

5.1 Flight Path Tool Implementation Status

The current development of this tool is considered satisfactory. It allows for the extraction of plausible flight paths from massive data, their representation, export to GIS, and height adjustment, if terrain is required (Figure 1).



(a) 2D trajectories.



(b) 3D trajectories.

Figure 1: 2D (a) and 3D (b) trajectories of Madrid-Barajas Airport, on June 27, 2022. Data source: OSN

However, the accuracy of noise calculations using ECAC Doc 29 is still unknown and requires further study. Since the ECAC Doc 29 developer volume does not include such comparison cases, it must be verified using available reference cases, such as the strategic noise maps prepared by the Kingdom of Spain for major airports [3].

5.2 Noise Calculation Tool Implementation Status

This section presents, on one hand, the analysis of the global results (calculated vs. reference) of SEL in the receiver grid (Grid SEL) and, on the other hand, the detailed evaluation of various parameters influencing Segment SEL (dB) (individual trajectories, acoustic corrections, elevation angles and directivity, etc.). The ECAC Doc29 criterion is employed, which recommends monitoring δ_{RMS} (root mean square of the differences) to assess the agreement between the model and the reference data.

5.2.1 Grid SEL Analysis

Looking at Table 1, we see that globally, an RMS Difference (δ_{RMS}) of approximately 1.19 dB (Figure 2) is presented for the entire set of cases, with a correlation of 0.9738 and a mean difference of 0.16 dB. This indicates that, although the overall dispersion may exceed 1 dB, the spatial trend of SEL is reproduced quite consistently.

Table 1: Comparison of Grid SEL Analysis.

Case ID	r	Mean dB Diff.	δ_{RMS}
Global results	0.9738	0.1591	1.1897
JETFAC	0.9945	-0.1153	0.5211
JETFAS	0.9934	-0.1406	0.5774
JETFDC	0.9576	0.3253	1.6169
JETFDS	0.9579	0.3191	1.6150
JETWAC	0.9940	-0.0387	0.5292
JETWAS	0.9939	-0.0408	0.5305
JETWDC	0.9581	0.3975	1.6350
JETWDS	0.9583	0.3766	1.6332
PROPAC	0.9982	-0.0013	0.2805
PROPAS	0.9982	-0.0040	0.2805
PROPDC	0.9688	0.3343	1.4129
PROPDS	0.9686	0.2947	1.4131

Examining each specific case, a differentiated behavior is observed between straight (S) and curved (C) trajectories. In straight paths (AS, DS) or approaches/takeoffs without turns, δ_{RMS} usually remains very low (0.28–0.58

[3] https://www.transportes.gob.es/aviacion-civil/medioambiente/mapas-estrategicos-ruido

dB in some cases), with mean differences < 0.15 dB. However, when the trajectory includes a curved segment (AC, DC), the RMS increases significantly (1.4–1.6 dB). This suggests that, although the model satisfactorily handles straight operations, turning maneuvers require further adjustments, particularly regarding thrust, bank angle, and lateral directivity.

Cases with propeller aircraft (PROP) show very low RMS in straight operations ($\leq$0.28 dB), indicating a high level of refinement for that aircraft type and flight profile. However, in curved operations, RMS increases to around 1.4 dB, consistent with jet trends. Nevertheless, the global correlations in all cases typically exceed 0.95, supporting the robustness of the model in terms of spatial noise pattern.

In summary, the values in the Grid SEL (dB) confirm that the general approach is valid, with the largest differences concentrated in trajectories with pronounced curves, where δ_{RMS} exceeds 1 dB and reaches 1.6 dB.

5.2.2 *Segment Parameters and Acoustic Factors*

To understand the potential sources of discrepancy in the calculated noise levels, we performed a detailed analysis of the parameters that determine the Segment SEL(dB), as shown in Table 2 (Geometric Analysis), Table 3 (Acoustic Corrections) and Table 4 (Segment SEL Analysis).

Table 2: Geometric Analysis: Calculated vs. Reference Data

Variable	r	Mean Diff.
λ (ft)	1.000	0.000
d_{p} (ft)	1.000	0.063
d_1 (ft)	1.000	0.343
d_2 (ft)	1.000	0.349
q (ft)	1.000	-0.171
Lat_{displ} (ft)	1.000	0.058
d_{NPD} (ft)	1.000	0.065
$Thrust_{\mathrm{P}}$ (lb/e)	0.993	-42.960
β (°)	0.573	-15.576
γ (°)	1.000	0.000
ϕ (°)	0.619	-12.705
θ_{bank} (°)	1.000	0.000

On one hand, the geometric distances (e.g., slant_distance, d_1, d_2, segment length λ, etc.) exhibit extremely high correlations (close to 1.0) and minimal mean differences.

Table 3: Acoustic Corrections: Calculated vs. Reference Data

Variable	r	Mean Diff.
$\mathrm{SEL_{base}}$ (dB)	0.997	0.245
$\Delta I(\phi)$ (dB)	0.739	-0.203
$\Lambda(\beta,\ell)$ (dB)	0.912	0.897
ΔV (dB)	0.976	0.740
ΔF (dB)	0.985	-0.979
ΔSOR (dB)	-	0.255
ΔImp (dB)	-	-0.070

This indicates that the positions of both the segment and the receiver are being represented with very high accuracy. However, the angles (i.e., β and ϕ) show lower correlations (about 0.57–0.62) along with average differences of around 10°–15° and standard deviations of 26°–29°. Because corrections such as lateral attenuation $\Lambda(\beta,\ell)$ and noise fraction ΔF depend strongly on these angles, even modest angular discrepancies tend to become amplified in the resulting acoustic calculations.

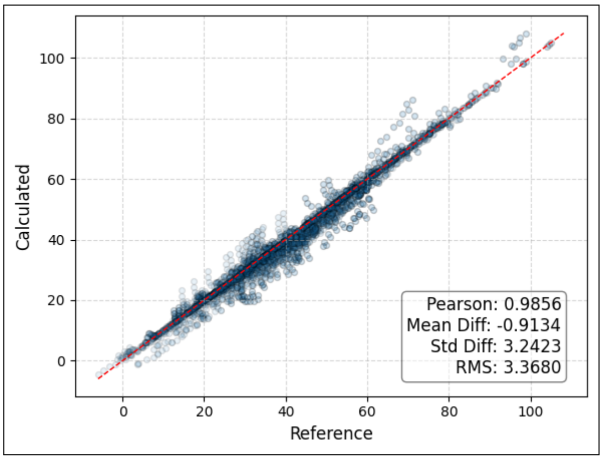
Table 4: Segment SEL Analysis: Calculated vs. Reference Data

Variable	r	Mean Diff.
δ_{RMS} (dB)	0.986	3.368
Mean Diff. (dB)	-	-0.913
Std Dev. (dB)	-	3.242

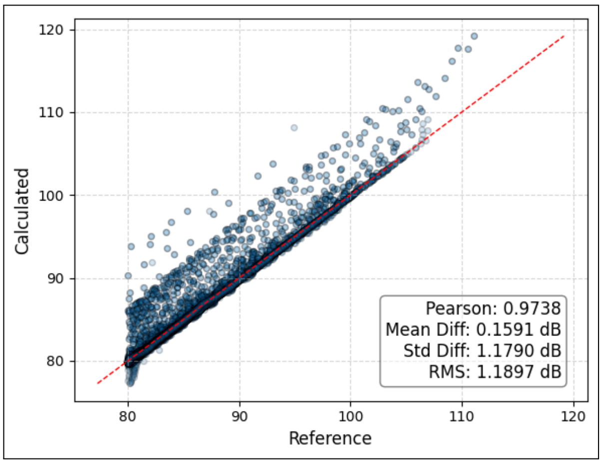
Regarding the acoustic corrections, the baseline SEL (the tabulated NPD reference) achieves excellent correlation ($\sim$0.997) but still exhibits a mean difference of about 0.24 dB, meaning that the overall NPD data are sound, but some residual inaccuracy remains when the final corrections are applied.

In addition, lateral attenuation and noise fraction show notably higher dispersion (with mean differences of $\sim$0.90 dB and $\sim$0.98 dB, respectively), consistent with the aforementioned angular issues. The engine installation correction $\Delta I(\phi)$ also introduces some scatter (correlation 0.739, mean difference ~ -0.20 dB) if the angles ϕ and β are not accurately captured. Finally, while the Segment SEL(dB) itself displays a very high correlation

(0.986), its δ_{RMS} of 3.37 dB indicates that some segments still deviate by a few decibels from their reference values (Figure 2a).



(a) Correlation Segment SEL(dB).



(b) Correlation Grid SEL(dB).

Figure 2: Correlation of Segment SEL(a) and Grid SEL(b) between reference and calculated results.

6. CONCLUSIONS

This work represents significant progress in the development of an open-source tool for large-scale aircraft noise assessment, in accordance with the guidelines of ECAC Doc. 29. The integration of two of its modules—the Flight Path Tool for data segmentation and the Noise Calculation Tool for calculating event noise levels—will allow for robust noise estimates.

This development currently presents reasonably good fits, especially for straight trajectories. In these cases, the model achieves very low RMS differences (often less than 0.6 dB) and high correlation coefficients, indicating the robustness of the basic methodology.

However, some challenges remain. On curved trajectories, δ_{RMS} differences tend to increase (reaching approximately 1.4−1.6 dB in grid analyses and even higher in segment-level assessments), primarily due to uncertainties in the estimation of angular parameters (elevation and directivity angles, β and ϕ). These angles are required for subsequent acoustic corrections (such as lateral attenuation and noise fraction), and even slight discrepancies in their values can be amplified, resulting in larger deviations in the final SEL calculations. Further refinement of the calculation of these angles is necessary to reduce these deviations and improve overall accuracy.

Looking ahead, tuning and calibration work is planned to improve the accuracy of the geometric and acoustic corrections, particularly in determining cases based on the relative position of the trajectory segment and the receiver, and corrections affected by angular parameters. Furthermore, the integration of noise segmentation and calculation modules into a unified framework is necessary to enable the agile use of big data.

Once finalized, the full code is intended to be made publicly available. This open-source tool is expected to not only advance the scientific assessment of aircraft noise at a general level, but also serve as a key resource to support the upcoming National Noise Strategy, thus contributing to more comprehensive and effective environmental noise management.

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