Revolutionising Noise Annoyance Quantification of Aircraft Landings through the Implementation of Tonality

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Aircraft noise annoyance during aircraft landings can be quantified and assessed by means of noise annoyance metrics. Knowledge of the behaviour of these metrics is therefore fundamental when assessing noise around airports. However, the most common certification metrics used nowadays were developed in the 1960s and consequently they are ~~obsolete and inadequate~~ to represent the acoustic annoyance of modern aircraft. This research aimed to analyse how the acoustic signature of the aircraft has evolved and whether the noise component of tonality plays a significant role nowadays. To research this, sound data from thirteen aircraft landings at Schiphol Airport have been recorded. Standard corrections have been applied ~~subsequently~~ when necessary and noise information at the source~~s~~ (aircraft) was obtained. In order to investigate the contribution of the tonality, three well established metrics for the quantification of the sound annoyance were compared to a new metric. This new metric ~~was developed including~~ the effect of tonality. ~~From this comparison,~~ it was observed that ~~while~~ the new metric ~~agreed~~ on which was the most annoying aircraft, it did differ on which ones were the least annoying. ~~Therefore,~~ the difference in ranking resulting from including tonality suggests that this noise component could indeed play an important role in modern aircraft noise annoyance.

Keywords: Aircraft noise annoyance; psychoacoustic annoyance; tonality; EPNL; A-weighted SPL; ~~Sound annoyance quantification~~

List of Abbreviations

A-W SPL	A-Weighted Sound Pressure Level
AAC	Atmospheric Absorption Coefficient
BNC	Background Noise Correction
DEC	Doppler Effect Correction
EPNL	Effective Perceived Noise Level
FS	Fluctuation Strength
GSC	Geometrical Spreading Correction
PA*	Psychoacoustic Annoyance with Tonality
PA	Psychoacoustic Annoyance

I. Introduction

Standing as a key environmental concern, aircraft noise is an ever-growing problem that will only ~~worsen~~ with time, as air traffic continues to grow rapidly every year [1]. ~~According to hospital admissions and mortalities experienced near Heathrow airport in London, aircraft noise can also lead to serious health issues~~ [2]. ~~This is, of course,~~ an inconvenience for the residents of any town in the vicinity of an airport. Based on the annoyance experienced by these residents, a few airports have started to put solution plans into action. At Amsterdam Schiphol Airport for instance, a Landscape Design Plan [3] including sound-reflecting ground bridges has been implemented, with the aim to reduce the noise experienced by the inhabitants of Hoofddorp Noord.

Although the implementation of this plan has positively impacted the community, it is currently ~~complex to determine whether an airport is in need of such a plan or not.~~ A central problem lies in the recording and processing of noise data of a landing airplane. If the noise emanating from an aircraft flyover were to be recorded from a ground-fixed microphone and analysed directly, the results would depict the noise at the receiver. By applying certain corrections, the noise data at the source can be obtained, which makes the comparison of different aircraft more reliable. A second core issue lies in quantifying annoyance experienced by humans. This is a subjective issue and can be approached with the use of several metrics to analyse the different elements of aircraft noise.

Concerning data corrections, no knowledge gap was found in the literature. The experiments described by Simons et al. [4], and Berckmans et al. [5] are leading in the correction for the Doppler effect. The method described by Snellen et al., [6] are used in the correction for the geometrical spreading and the background noise. Finally, atmospheric absorption was accounted for by using the methods described by Lamancusa [7]. Concerning the metrics used to analyse the corrected data however, a significant knowledge gap was found in the literature: the influence of tonality is ~~indeed~~ not considered in present-day metrics for psychoacoustic annoyance. The methods described in [8], [9], [10], and [11] are adopted to investigate A-Weighted Sound Pressure Level (A-W SPL), Effective Perceived Noise Level (EPNL), loudness, sharpness, roughness and fluctuation strength. ~~The first two of these~~ are used for comparison directly, while the last four are combined into the old psychoacoustic annoyance metric.

The purpose of this work is to compare three existing metrics, namely the EPNL, the A-W SPL, and the classical psychoacoustic annoyance, ~~to~~ a new extended version of psychoacoustic annoyance, implementing the influence of tonality. This influence was computed ~~with the~~ method described in [8].

The article opens with a description of the data available (section II). It proceeds with a comprehensive discussion on the corrections and metrics employed (section III) after which the results of the research are shown along with the most important outcomes of the data processing (section IV). Finally, some conclusions based on the results and recommendations for further research are presented (section V).

II. Data Description

Sound pressure data of thirteen aircraft landings at Amsterdam Schiphol Airport were recorded with an array of microphones, placed on the ground, at a sampling frequency of $40,000$ Hz for time intervals varying between 20 and 25 seconds. For the present research, the data from just one of these microphones was used. By means of an optical camera, the altitude~~s~~ and the speed~~s~~ of the aircraft during flyovers were computed, making it possible to determine the landing trajectory and the time of overhead passage.

III. Methodology

~~The following method was developed for analyzing the provided data:~~ a number of corrections were first applied to the provided data when necessary, namely for the background noise, Doppler effect, geometrical spreading and atmospheric absorption. By doing this, ~~the aircraft noise~~ was traced back to ~~its~~ source, allowing for an accurate comparison between the different aircraft landings' spectrograms. Following this, the afore-mentioned metrics were ~~then~~ investigated and combined, which resulted in four main metrics that could then be compared. The first three chosen metrics were the EPNL, the A-W PNL, and the PA, which were the main ones used in the past to quantify noise annoyance. The fourth metric was a modified version of the PA that took into account the tonality metric and was hence named "Psycohacustic Annoyance with Tonality" (PA*). A graphical summary of the process undergone can be found in Fig. 1.

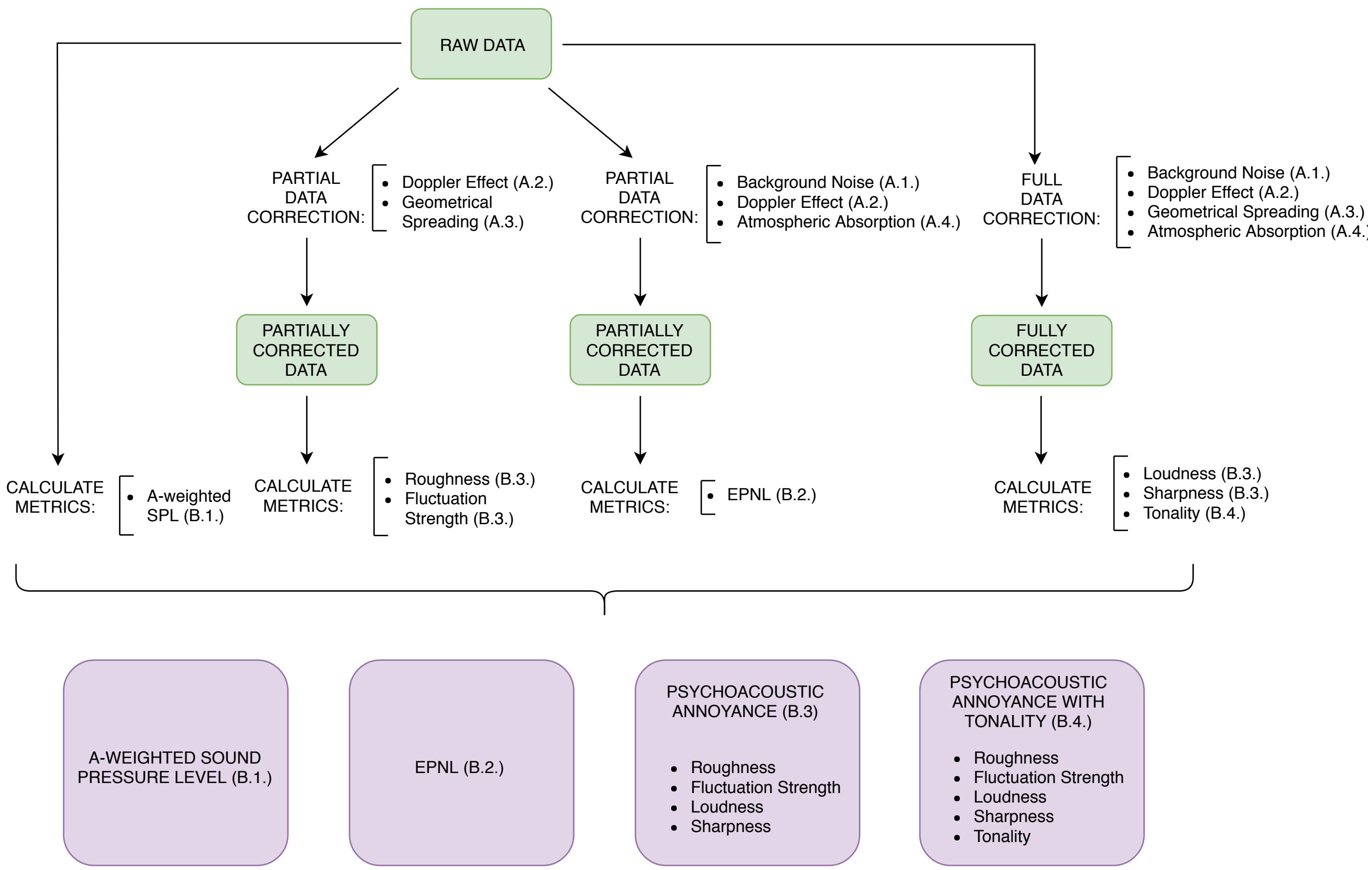


Figure 1: *Graphical representation of the followed method.*

A. Data Corrections

Data correction deals with the problem of sound recording being affected by the variations in aircraft's position and speed, atmospheric absorption, and background noise. These corrections were performed to obtain the sound data at the source. This enabled a proper comparison between aircraft flyovers. ~~Moreover, no correction for wind gradients, temperature gradients nor surface effects were implemented, as the Doppler effect correction already accounted for the aircraft's individual movements.~~

1. ***Background Noise Correction*** *(BNC)*

BNC was applied by subtracting the spectrogram of the background noise from the spectrogram of the recorded flyover. The spectrogram of the background noise was obtained by processing a recording from the microphone in a time interval when no aircraft was in range. Although this method exploited the well proven principle of superposition, as the two recordings had in fact not been taken at the same instant in time, the subtraction resulted solely in an approximation. This uncertainty mostly deteriorated the information at low powers and thus the sound pressure levels (SPL) below 30 dB had been filtered out. Furthermore, a 4th order high-pass Butterworth filter was used to filter out the lower frequencies caused by the background noise. The cutoff frequency was set to 300 Hz, which implied that only the frequencies above this were kept in the data.

2. ***Doppler Effect Correction*** *(DEC)*

DEC was used to obtain the frequency emitted at the source, given the frequencies recorded by the microphone. Eq. (1) describes this phenomenon.

$$f = \frac{f'}{(1 + \frac{V}{c})} \tag{1}$$

Here f' is the observed frequency, f is the emitted frequency at the source, V is the speed of the aircraft relative to the microphone and c the speed of sound. Since the aircraft was assumed to be flying over at a specific height, its speed relative to the microphone could be represented by Eq. (2), where V_0 is the aircraft's speed and θ the acute angle between the ground plane and the distance between the microphone and the aircraft.

$$V = V_0 \cdot cos(\theta) \tag{2}$$

3. ***Geometrical Spreading Correction*** *(GSC)*

GSC had to be applied, as it was also necessary to compensate for the variable distance between the aircraft and the microphone resulting from the aircraft movement. To account for these variations, the position of the aircraft was first determined at each recorded data point and stored in terms of x and y coordinates (because of the nature of the flyover, the flight could be assumed to be two dimensional). The distance r between the microphone and the aircraft was then computed for each data points and Eq. (3) was used to correct each data point accordingly.

$$SPL_{r_0}(f) = SPL(r, f) + 20 \cdot log\left(\frac{r}{r_0}\right) \tag{3}$$

Here $SPL(r, f)$ is the SPL at the receiver and $SPL_{r_0}(f)$ is the SPL at the source. Applying this correction allowed to retrace the sound signal back to the source and virtually "place" the microphone at a defined distance r_0 (decided to be $r_0 = 1$) from each aircraft at all times during recording. The spectrogram was only reliable for the interval of time during which the aircraft was directly overhead the microphone. This limitation was due to the fact that the microphone used was not perfectly omnidirectional and precise information of its directionality pattern was unavailable.

4. ***Atmospheric Absorption Correction*** *(AAC)*

AAC is essentially a function of two variables. One is the distance between the noise source (aircraft) and the receiver (microphone), r, and the other is the so-called "atmospheric absorption coefficient", α, which was, in turn, a function of the frequency, f, the temperature, T, relative humidity and the static pressure of the atmosphere. However, the relative humidity, static pressure and temperature were considered a constant, making alpha a function of frequency only. The absorption term could be added to Eq. (3), yielding Eq. (4).

$$SPL_{r_0}(f) = SPL(r, f) + 20 \cdot log\left(\frac{r}{r_0}\right) + \alpha(f) \cdot r \tag{4}$$

The atmospheric absorption coefficient, $\alpha(f)$, was found using Eq. (5) to Eq. (7), [7]. Here, T is the temperature of the atmosphere in which the computation is done, 293.15 K, T_0 is a reference temperature, which is also equal to 293.15 K, h is the relative humidity and was equal to 70 % in this work and f is the frequency. The relations are valid for a static pressure of 1 atm, which is equivalent to measurement conditions.

$$\alpha = 869 \cdot f^2 \cdot \left\{1.84 \cdot 10^{-11} \cdot \left(\frac{T}{T_0}\right)^{\frac{1}{2}} + \left(\frac{T}{T_0}\right)^{\frac{-5}{2}} \cdot \left[0.01275 \cdot \frac{e^{\frac{-2239.1}{T}}}{F_{r,o} + f^2/F_{r,o}} + 0.1068 \cdot \frac{e^{\frac{3352}{T}}}{F_{r,N} + f^2/F_{r,N}}\right]\right\} \tag{5}$$

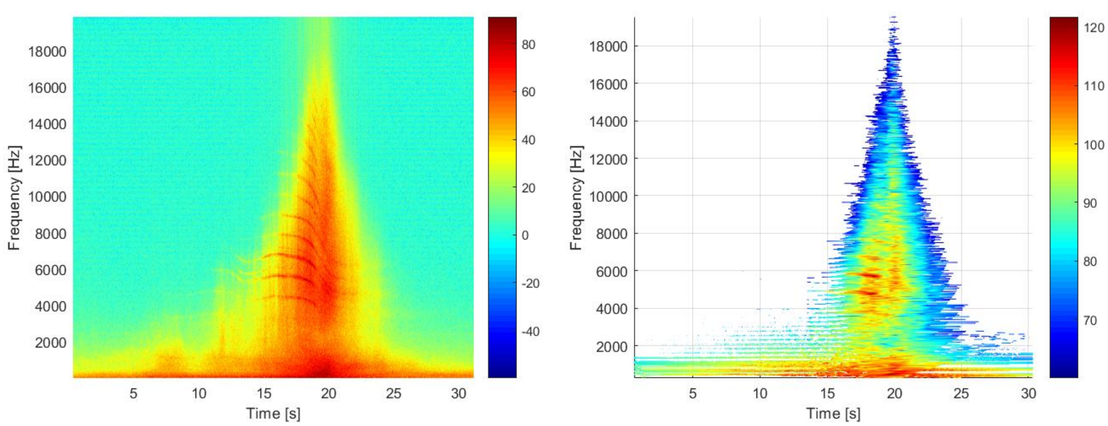
In Eq. (5) $F_{r,o}$ and $F_{r,N}$ are given by Eq. (6) and Eq. (7). They represent the oxygen and nitrogen relaxation frequencies respectively.

$$F_{r,o} = 24 + 4.04 \cdot 10^4 \cdot h \cdot \frac{0.02 + h}{0.391 + h} \tag{6}$$

$$F_{r,N} = \left(\frac{T}{T_0}\right)^{\frac{-1}{2}} \cdot \left[9 + 280 \cdot h \cdot e^{\left\{-4.17 \cdot \left[\left(\frac{T}{T_0}\right)^{\frac{-1}{3}} - 1\right]\right\}}\right] \tag{7}$$

5. ***Spectrograms after data correction***

The differences between the corrected and the uncorrected spectrograms can be observed in Fig. 2.



(a) *Uncorrected Spectrogram* (b) *Corrected Spectrogram*

Figure 2: *Aircraft 7*

In Fig. 2b, it can be seen that the noise levels are higher than in Fig. 2a. This is to be expected as the corrected spectrogram resembled the noise at the source. Furthermore, it is clear that the background noise was eliminated in the spectrogram after corrections. Lastly, it is observed that the lines of higher power in Fig. 2a went from a curved shape to more straight lines in Fig. 2b. This is a direct consequence of the Doppler effect correction.

B. Metrics Computation

Different types of sound attributes are responsible for the annoyance felt by a human ear during an aircraft flyover or landing. The metrics used in this research will be discussed in the following subsections.

*1. **A-Weighted Sound Pressure Level** (A-W SPL)*

A-weighted sound pressure level is the simplest metric for noise assessment as compared to the other main metrics. It is implemented on the observed noise, the signal without the corrections. It quantifies the annoyance by taking into account the impact of different frequencies to the observer as some frequencies can be perceived as being louder. The filter applies a correction for each frequency and is given by Eq. (8), [12], as mentioned by Ruijgrok.

$$\Delta L_A = -145.528 + 98.262 \cdot \log(f) - 19.509 \cdot (\log(f))^2 + 0.975 \cdot (\log(f))^3 \tag{8}$$

Here ΔL_A is the attenuation and f is the frequency. This approximation was derived from the inverted equal loudness contour of 40 phon. Fig 3 displays the weighting curves for A-weighting correction (smooth line), and C-weighting correction (dashed line). The smooth line annotated as “A” is a plotting of Eq. (8). It can be seen that this filter dampens the lower frequencies. ΔL_A was then found for every frequency band using f as the central frequency of said band. This correction was then added to the average sound pressure level, SPL for the corresponding frequency band as shown in Eq. (9):

$$L_A(i) = SPL(i) + \Delta L_A(i) \tag{9}$$

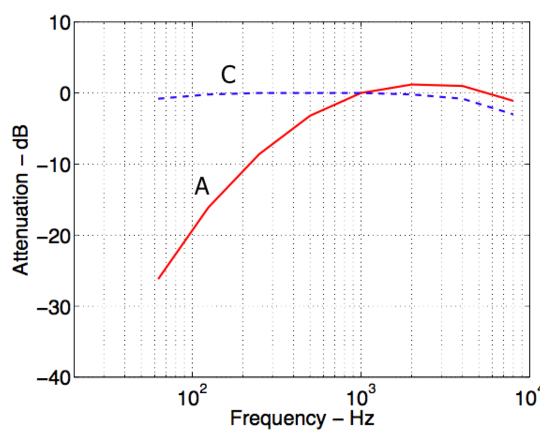


Figure 3: *A and C weighting curves [10]*

Here $L_A(i)$ is the corrected SPL for a frequency band. Finally, the overall A-W SPL was calculated by summing up all the $L_A(i)$ for the entire frequency range of the signal in one time step. This was done with Eq. (10).

$$L_A = 10 \log \sum 10^{\frac{L_A(i)}{10}} \tag{10}$$

L_A, the overall A-W SPL is expressed in dBA as a unit. If L_A is found for each time step for the entire time interval of the signal, a graph of L_A against time can be plotted. To compare the signal of one aircraft to another, the maximum $L_A(i)$ for a signal is found. This is typically the value at which the aircraft is directly overhead. Here, signal comprises of mostly the higher frequencies thus it is not as dampened as when the aircraft is approaching or leaving the observer, when the signal contains mostly low frequencies.

2. ***Effective Perceived Noise Level*** *(EPNL)*

Another metric used was the effective perceived noise level, a scale developed by K.D. Kryter in 1959 and described in “Aircraft Noise Evaluation” [9]. EPNL, measured in decibels (dB) is based on the sound pressure level data and is similar to loudness. The difference is that EPNL is also further corrected for the irregularities in the spectrum of the sound (tones) and the duration of the sound. EPNL is considered as one of the simpler metrics and it was decided to include it in the research to compare the results with the more complex metrics.

The analysis was performed separately for every time step and in the end, the values of perceived noise level per step were integrated over time resulting in one value of EPNL. The first step was to calculate the Average Sound Pressure Level (ASPL) using the technique described in section III (loudness). After the ASPL was obtained, the number of noys had to be calculated based on the magnitude of the ASPL in each band. A further explanation of this analysis can be found in [13]. Noys are a different way of quantifying the loudness and the advantage is that this scale accounts for the annoyance response of human ear as a function of frequency. Finally, the noys from each band were combined into the total number of noys with Eq. (11) and then converted back to decibels with Eq. (12) which resulted in the perceived noise level, denoted as PNL.

$$N_{tot} = 0.85 \cdot N_{max} + 0.15 \cdot N_{sum} \tag{11}$$

$$PNL = 40 + \frac{10}{log_{10}(2)} \cdot log_{10}(N_{tot}) \tag{12}$$

The next step was to find the tone correction factor which is based on the magnitude of the tonal components of the sound. This was a rather lengthy procedure, thus, for more detailed information refer to “Aircraft Noise Evaluation” [9]. The factor was subsequently added to the PNL resulting in tone corrected perceived noise level (PNLT). Lastly, the values of PNLT in every time step were summed together with Eq. (13) , resulting in the value of EPNL.

$$EPNL = 10 \cdot log_{10}\left(\sum_{k=0}^{t} antilog\frac{PNLT(k)}{10}\right) - 13 \tag{13}$$

3. ***Psychoacoustic Annoyance*** *(PA)*

Psychoacoustic annoyance relates physical quantities of sound and subjective hearing impressions, as mentioned by HeadAcoustics [14]. It is the result of a combination of different sound metrics which include roughness, fluctuation strength, loudness and sharpness. Each of these sound metric will be discussed in the following subsections. The use of this metric enabled to predict the annoyance effectively, focusing more on the “human perception”. The equation describing PA, taken from E. Zwicker [15] is given by Eq. (14).

$$PA = N \cdot \left(1 + \sqrt{W_S^2 + W_{RF}^2}\right) \tag{14}$$

Equation (14) depends on loudness N expressed in phons, W_S, and W_{RF} which depend on sharpness S in acum, roughness R in asper, and fluctuation strength F in vacil. The formulae that describe these two parameters are given in Eq. (15) and Eq. (16).

$$W_S = \begin{cases} 0 & S \leq 1.75 \\ (S - 1.75) \cdot 0.25 \cdot \log(N + 10) & S > 1.75 \end{cases} \tag{15}$$

$$W_{RF} = \frac{2.18}{N^{0.4}} \cdot (0.4 \cdot F + 0.6 \cdot R) \tag{16}$$

In the second column of the table 3 in Appendix C, it can be observed that none of the sharpness values was higher than 1.75 acum. Furthermore, Eq. (15) states that if sharpness is less than 1.75 acum, W_S is equal to 0. Therefore, the main parameters governing the PA equation for all the aircraft cases were loudness, roughness and fluctuation strength. A more in-depth sensitivity study can be found in Appendix A. The following subsections discuss the sound metric components used in the above equations.

Loudness

According to Sahai [16], loudness is understood to be the sensation of sound volume as perceived by humans.

Loudness is a subjective perception and is thus not to be confused with physical values such as the Sound Pressure Level (SPL), which is a logarithmic measure of the effective pressure caused by a sound wave. Loudness, expressed as N, is visualised in a logarithmic scale and it is represented by a unit called "phon". As can be seen in Fig. 4, sounds of certain frequencies and SPLs can be perceived as having the same loudness (the equal-loudness contours from ISO 226:2003 [17]). The calculation of loudness started with sorting the data points into twenty-four 1/3 octave frequency bands. The twenty-four bands cover the frequencies the equal-loudness contours are made for. Then, the average sound pressure level (ASPL) was calculated for every band using all the data points. Subsequently, using data from ISO 226:2003 [17], a table was made with values of phon which corresponded to certain SPLs at all the bands. Using this table and the ASPL of each band, the phon of each band could be found. An average of all the bands was calculated as a value of loudness. These phon values could then be used in further metrics.

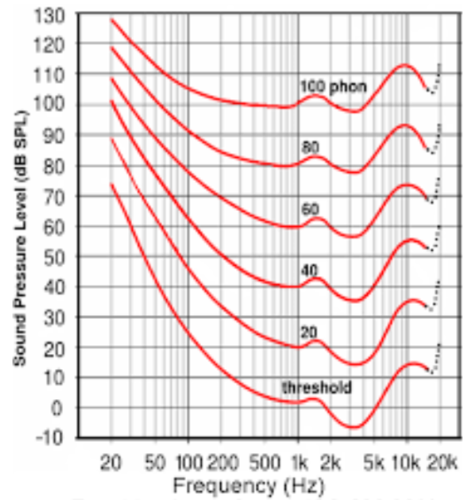


Figure 4: *Equal-loudness Curve [17]*

Sharpness

For a given frequency, the computation of the sharpness metric depended on the corresponding value of loudness N. The higher the value of sharpness, the more annoying it is, as it represents the measure of the high frequency elements of a sound. To compute the sharpness, the critical band z was calculated using Eq. (17). For each band z, the weighted first moment $g(z)$ had to be determined with Eq. (18).

$$z = 13 \cdot \tan^{-1}(0.76 \cdot \frac{f}{1000}) + 3.5 \cdot \tan^{-1}(\frac{f}{7500})^2 \tag{17}$$

$$g(z) = \begin{cases} 1 & , z \leq 16 \\ 0.066 \cdot e^{0.171z} & , z > 16 \end{cases} \tag{18}$$

Following this, the product of the first moment $g(z)$, the derivative of the loudness function $N'(z)$ and z itself was integrated between 1 and 24, using numerical integration, which corresponded to the first twenty-four 1/3 critical bands of hearing. Equation (19) was then used to compute a final value of the sharpness S, where the proportionality constant u depends on the normalization of the reference sound. This value is typically taken to be equal to $u = 0.11$, as advised in Zwicker and Fastl's sharpness model [15]. In Eq. (19) the integral was computed by with a numerical integration, as the domain was discrete. Depending on all the frequencies recorded during a certain aircraft flyover, a value for sharpness was yielded, which could then be used to evaluate the sharpness footprint of every aircraft.

$$S = u \cdot \left[\frac{\int_0^{24} g(z) \cdot N'(z) \cdot z dz}{N} \right] \tag{19}$$

Roughness

Roughness, expressed in asper, represents the measure of the unpleasant sensation of fluctuation in the sound, caused by the rapid amplitude modulation at frequencies between 15 Hz and 300 Hz. To calculate the roughness, use was made of the mirToolbox for MATLAB from the University of Jyvaskyla [18]. Roughness was obtained using the function "mirroughness", while using the weighted "Vassilakis" method (described in the program itself). The required input was the audio signal of the landing airplane. Eq. (20) was used to calculate roughness:

$$R = 0.3 \cdot \frac{f_{mod}}{kHz} \cdot \int_0^{24} \frac{\Delta L_E(z)}{dB/Bark} dz \tag{20}$$

In this equation, f_{mod} is the modulation frequency and ΔL the temporal masking depth. These two parameters are described in Fig. 5. The aircrafts passing at different heights resulted in the roughness calculation being influenced by the geometric dissipation of the sound. The geometrical spreading correction therefore had to be applied here. A Doppler correction needed to be applied as roughness depends deeply on the frequency of the aircraft sound which was impacted by the Doppler effect.

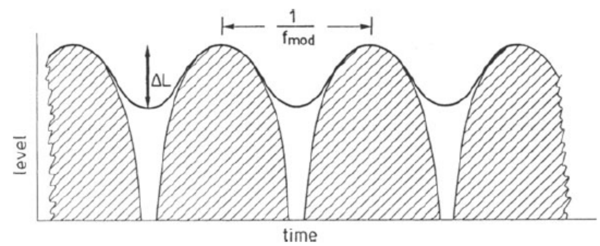


Figure 5: *Modulation frequency and temporal masking depth representation.*

***Fluctuation Strength** (FS)*

The fluctuation strength metric is complementary to the roughness one, as it quantifies the subjective perception of slower (up to 20Hz) amplitude modulation of the sound. The sensation of fluctuation strength persists indeed up to 20Hz, where the sensation of roughness takes over.

Fluctuation strength was calculated with the same MATLAB toolbox from the University of Jyväskylä [18] used for the roughness calculations. This toolbox includes a function called "mirspectrum": by specifying the temporal masking depth and the modulation frequency, a value quantifying fluctuation could be obtained through the use of Eq. (21).

$$FS = \frac{0.008 \cdot \int_0^{24} \Delta L/dB \, dz}{(f_{mod}/4Hz) + (4Hz/f_{mod})} \tag{21}$$

Similar to roughness, the geometrical spreading and the Doppler corrections also had to be applied.

4. Psychoacoustic Annoyance with Tonality (PA)*

Tonality greatly influences the annoyance experienced by the listener. Unfortunately, tonality is conventionally not included in Eq. (14). Thus, a new psychoacoustic annoyance formula was developed, including tonality. Before adding it, a sensitivity study was conducted. Tonality can take values from 0.1 to 0.5 t.u.. In order to include tonality in the PA calculation, it was suggested by Schneider [11] to use Eq. (22):

$$PA^{*} = N \cdot \left(1 + \sqrt{W_S^2 + W_{RF}^2}\right) \cdot (0.25 \cdot K + 1) \tag{22}$$

Here PA* is the recalculated PA, and K is the tonality. Tonality is discussed in the subsection below. The 0.25 value included in the formula reduced the influence of tonality. Including tonality could thus increase the PA from 2.5% to 12.5%.

Tonality

Tonality is considered to be the second biggest contribution to the phenomenon of annoyance, after loudness [8]. It is an indication of the presence of components with small frequency bandwidths that have a higher power than their neighbouring frequencies. These small bandwidths are more annoying, than bigger bandwidths with a higher power than their neighbouring frequencies. To determine the annoyance of the presence of these components, Aures' tonality method [19] was used. Higher values indicate more annoyance due to tonality in this metric.

The tonal components were first determined. These are pure tones or narrowband noises ranging from 100 to 150 Hz, that exert 7 dB more than the levels of all neighbouring narrowband samples. They were determined by hand due to the complexity of the components, and the inability to develop an analytical method. As a result of subjectivity, the accuracy dropped.

Next, the effect of bandwidth, frequency and prominence of the individual tonal components were calculated and converted to an overall tonal weighting function. The formulae needed to calculate this weighting function and a loudness weighting function are shown in section V. Finally, this was used into Eq. (23) for tonality.

$$K = c_k \cdot w_T^{0.29} \cdot w_{Gr}^{0.79} \tag{23}$$

In this equation, K is the tonality expressed in t.u., c_k is a calibration constant, w_T is the overall tonal weighting function and w_{Gr} is the loudness weighting function. Finally, the median of the tonality over time was chosen as the tonality of the aircraft.

IV. Results and Discussion

The methods described above for correcting the investigated signal and computing the different metrics were compiled in a MATLAB program, making it possible to treat the large amount of data efficiently and quickly (Appendix V). Upon running the data through it, it was possible to rank aircraft according to their different sound characteristics. A ranking was determined for EPNL and A-W SPL. Psychoacoustic annoyance was then investigated to provide the link between the physics of the sound and the subjective human perception and reaction, once excluding the tonality in the calculations and once including it.

A summary of the different rankings obtained is provided below. In Tables 1, 2, **??** and **??** red represents the most annoying aircraft landing, and dark orange the second to most annoying one. Green represents the least annoying, and yellow the second least annoying one. All light orange values are the ones standing in between.

Table 1: *Noise annoyance of analyzed aircraft quantified by means of the A-W SPL metric.*

Aircraft	A-W SPL $[dBA]$
1	88.23
2	90.24
3	92.78
4	90.30
5	89.18
6	86.78
7	87.75
8	89.69
9	86.88
10	85.57
11	85.14
12	89.25
13	87.52

Table 2: *Noise annoyance of analyzed aircraft quantified by means of the EPNL metric.*

Aircraft	EPNL $[EPNdB]$
1	165.79
2	172.37
3	200.38
4	183.50
5	169.50
6	173.94
7	166.03
8	186.19
9	199.17
10	177.60
11	176.32
12	199.81
13	176.76

Table 3: *Noise annoyance of analyzed aircraft quantified by means of the Psychoacustic Annoyance metric.*

Aircraft	Loudness $[phon]$	Sharpness $[acum]$	Roughness $[asper]$	F. S. $[vacil]$	**PA**
1	139.73	1.65	2.78	1.85	**0.986**
2	139.59	1.65	2.28	1.77	**0.967**
3	140.29	1.56	3.69	1.31	**1.00**
4	139.71	1.65	2.94	1.57	**0.932**
5	139.24	1.74	3.19	1.58	**0.965**
6	139.59	1.65	3.13	2.00	**0.956**
7	139.43	1.65	2.40	1.32	**0.949**
8	139.69	1.65	2.35	1.82	**0.996**
9	139.62	1.65	3.13	1.25	**0.970**
10	139.52	1.65	2.58	1.66	**0.974**
11	139.42	1.65	2.33	1.27	**0.979**
12	140.05	1.56	2.63	1.43	**0.972**
13	139.55	1.65	2.93	1.38	**0.982**

Table 4: *Noise annoyance of analyzed aircraft quantified by means of the Psychoacustic Annoyance with Tonality metric.*

Aircraft	Loudness [*phon*]	Sharpness [*acum*]	Roughness [*asper*]	F. S. [*vacil*]	Tonality [*t.u.*]	**PA***
1	139.73	1.65	2.78	1.85	0.15	**0.951**
2	139.59	1.65	2.28	1.77	0.26	**0.967**
3	140.29	1.56	3.69	1.31	0.30	**1.00**
4	139.71	1.65	2.94	1.57	0.07	**0.932**
5	139.24	1.74	3.19	1.58	0.21	**0.965**
6	139.59	1.65	3.13	2.00	0.14	**0.956**
7	139.43	1.65	2.40	1.32	0.20	**0.949**
8	139.69	1.65	2.35	1.82	0.38	**0.996**
9	139.62	1.65	3.13	1.25	0.24	**0.970**
10	139.52	1.65	2.58	1.66	0.28	**0.974**
11	139.42	1.65	2.33	1.27	0.34	**0.979**
12	140.05	1.56	2.63	1.43	0.26	**0.972**
13	139.55	1.65	2.93	1.38	0.30	**0.982**

Once the ranking for the four analysed metrics had been determined, comparing them allowed to gain insight on the significance of the different components (such as tonality) and whether the obtained results varied.

To ease comparison, the values displayed in Table 5 are a fraction of the maximum value, the maximum being equal to 1.00 for each result set and all other being expressed as a fraction of it.

Table 5: *Results for A-W SPL, EPNL, PA, and PA* expressed as fractions of the respectively highest values.*

Aircraft	A-W SPL	EPNL	PA	PA*
1	0.951	0.827	0.986	0.951
2	0.973	0.860	0.976	0.967
3	1.000	1.00	1.000	1.000
4	0.973	0.916	0.985	0.932
5	0.961	0.846	0.986	0.965
6	0.935	0.868	0.993	0.956
7	0.946	0.829	0.972	0.949
8	0.967	0.929	0.974	0.996
9	0.936	0.994	0.984	0.970
10	0.922	0.994	0.979	0.974
11	0.918	0.880	0.970	0.979
12	0.962	0.997	0.981	0.972
13	0.943	0.882	0.982	0.982

Overall, all four rankings placed aircraft number 3 as the most annoying one. The predictions for the second most annoying however were much less consistent, with none of the rankings agreeing on a single aircraft. When it came to the second least annoying aircraft, A-W SPL was the only ranking standing out, the other three placing aircraft 7 as second least annoying. Finaly, A-W SPL and PA without Tonality were the only ones to agree on the same aircraft (Table 5).

Overall, Psychoacoustic annoyance alone delivered results sharing more similarities with A-W SPL and EPNL than Psychoacoustic annoyance with Tonality. This suggests that Tonality could plays a large role in modern aircraft noise, resulting in this difference in ranking.

According to More [10], normal values for the **tonality** of aircraft noise range between 0.1 and 0.4 t.u.. Aircraft 4 presented a value below 0.1 t.u.. A tonal component should be a bandwidth with higher SPL than its neighbouring frequencies. In the spectrogram corresponding to Aircraft 4, it was observed that during the time of the flyover, there was no clear pattern of straight lines visible, due to the corrections. The tonality could therefore not be determined clearly in this case. Due to the determination of tonal components by hand, the accuracy of the results is to be debated. However, because this method was used consistently for all the flyovers, the aircraft results could be compared and the impact of tonality analysed.

For **A-weighting sound pressure level** a note should be made. As stated by More [10], although this metric is widely used, it is insufficient as a tool to assess aircraft noise effectively. This is due to the fact that the weighted filter for this metric is derived from the 40 phons equal loudness contour, while it was determined through calculations performed by the program (as seen in column for Loudness in Table 3) that most of the aircraft signal were at around 140 phons.

A final note should be made on the trend which was observed when comparing the metrics annoyance ranking with the respective speed of each aircraft. When looking at the individual metrics ranking (visible in Table 4), a strong positive correlation was found relating speed to sound annoyance.

V. Conclusions and Recommendations

The purpose of this work was to compare three existing metrics, namely the EPNL, the A-W SPL, and the classical psychoacoustic annoyance, to a new extended version of psychoacoustic annoyance, implementing the influence of tonality. First, the raw signals were corrected when necessary, as the original recording did not show the true sound pressure data of the aircraft. Secondly, several metrics were calculated, some served directly for comparison while the others were combined into the PA and PA*. Finally, a comparison of the four main metrics was done.

From the final comparison, it was observed that all the metrics agreed on which was the most annoying aircraft while they differed on which one was the least annoying. The difference in ranking resulting from including tonality suggests that this noise component could play an important role in modern aircraft noise. Another interesting trend was found upon comparing the results with the speed of the landing aircraft. It was observed that the annoyance proposed by the metrics increases as the aircraft approach speed increases.

For further research, it would be helpful to investigate the annoyance level experienced by a randomized group of individuals when listening to the thirteen aircraft landing recordings, in order to investigate the applicability of the models. Making a final ranking of the aircraft, and exploring the elements that make them more or less annoying would enable for better annoyance quantification and accuracy. Further exploring the role and evolution of tonality in modern aircraft would provide useful insight on the relevance of this potential new model and enable better quantification of noise annoyance. Finally, it is suggested to investigate the correlation between landing speed and perceived noise annoyance.

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Appendix A

This Appendix will include the sensitivity study of the psychoacoustic analysis (PA) equation, to understand how each parameter alters the final result individually. The PA equation used was:

$$PA = N \cdot \left(1 + \sqrt{((S-1.75)\cdot 0.25 \cdot \log(N+10))^2 + (\frac{2.18}{N^{0.4}} \cdot (0.4 \cdot F + 0.6 \cdot R))^2}\right) \cdot (0.25 \cdot T + 1) \tag{24}$$

A geometric representation of Eq. (14) is displayed in Fig. 6. Here, the two terms W_S and W_{RF} form the cathetus of a right-angled triangle. Therefore, if there exists a big difference between the two, the bigger term will be the leading one. For example, if we assume a really high value of W_S compared to W_{RF}, the leading term is W_S.

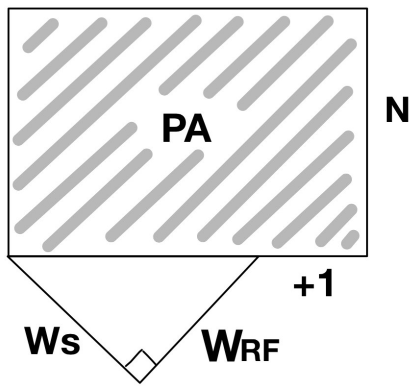
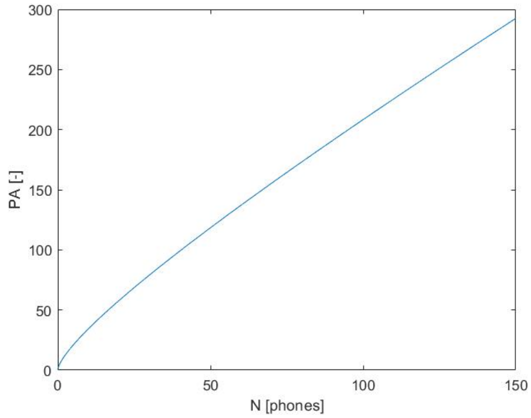


Figure 6: Geometric representation of Psychoacoustic Annoyance Equation.

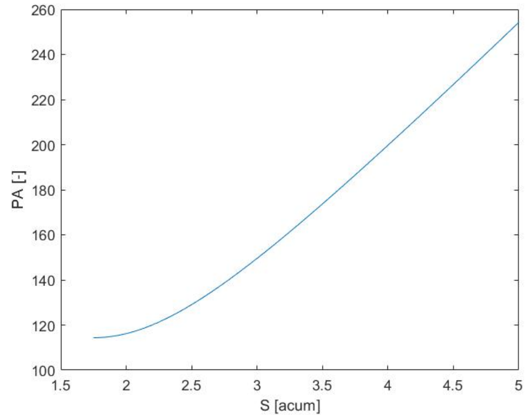
Reference values where extracted from TU Delft publication [20] in order to analyse the equation:

- Loudness: 47.9 [phons], Boundaries: 0 - 150
- Sharpness: 0.952 [acum], Boundaries: 0 - 5
- Tonality: 0.194 [-], Boundaries: 0 - 0.5
- Roughness 2.66 [asper], Boundaries: 0 - 10
- Fluctuation Strength: 1.4 [vacil], Boundaries: 0 - 10

Now it was possible to conduct the sensitivity study by fixing all the variables but one to a single value. The spare variable was the independent variable while PA was always be the dependent variable. The independent variable boundary conditions were specified to create a plausible model. With the values extracted from [20], it was found that $\boldsymbol{PA = 131.8}$. Figures 7 and 8 represents the change in PA while increasing the other variables. It can be observed that loudness is the leading term of the equation. It is the only variable that when equal to 0, makes the overall PA equal to 0 as well.

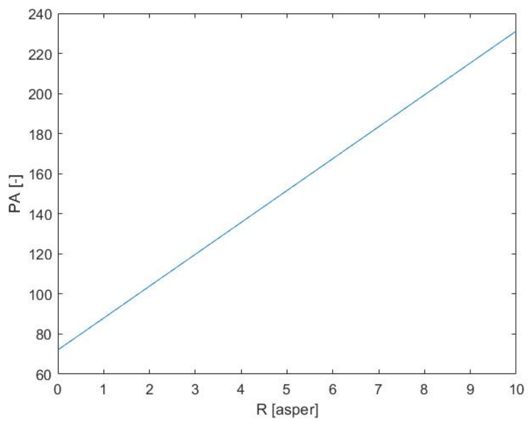


(a) PA vs. Loudness

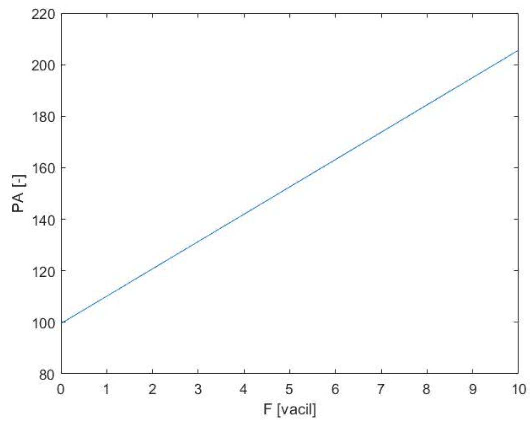


(b) PA vs. Sharpness

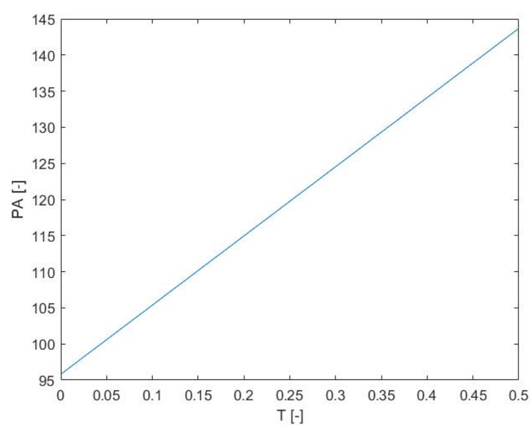
Figure 7: Comparison of the influence of loudness and sharpness on PA



(a) PA vs. Roughness



(b) PA vs. Fluctuation strength



(c) PA vs. Tonality

Figure 8: Comparison of the influence of roughness, fluctuation strength and tonality on PA

Appendix B

This Appendix will include all the formulas used in Aures method to calculate Tonality.
The influence of bandwidth was based on the Sound Pressure Level excess, ΔSPL_i, of the tonal components, which was calculated with Eq. (25):

$$\Delta SPL_i = SPL_i - 10\log_{10}\left\{\left[\sum_{k\neq i}^{n} A_{Ek}(f_i)\right]^2 + E_{Gr}(f_i) + E_{HS}(f_i)\right\} \tag{25}$$

In this equation, SPL_i is the actual SPL for the i^{th} tonal component, A_{Ek} is the influence of the tone on the other tonal components, E_{Gr} is the masking intensity of the noise surrounding the i^{th} tone and E_{HS} is the intensity at the threshold of hearing. When the resulting ΔSPL_i was lower than 0, it was neglected. A_{Ek} was calculated with the following formulas, where k is any tonal component except for i and z were calculated with Eq. (17).

$$s = \begin{cases} 27 & f_i < f_k \\ -24 - \frac{230}{f_k} + 0.2 \cdot SPL_k & f_i > f_k \end{cases} \tag{26}$$

$$SPL_{Ek}(f_i) = SPL_k - s \cdot (z_k - z_i) \tag{27}$$

$$A_{Ek}(f_i) = 10^{\frac{SPL_{Ek}(f_i)}{20}} \tag{28}$$

This was calculated for all other tonal components and added up together in Eq. (25). E_{HS} was calculated with Eq. (29):

$$E_{HS}(f_i) = 3.64 \cdot \frac{f_i}{1000}^{-0.8} - 6.5 \cdot e^{-0.6(\frac{f_i}{1000}-3.3)^2} + 10^{-3}\Big(\frac{f_i}{1000}\Big)^4 dB \tag{29}$$

E_{Gr} is the masking intensity and was calculated as the sum of the broadband noise intensities around the tone. This region was defined from $z_i - 0.5$ Bark to $z_i + 0.5$ Bark. After the ΔSPL_i was calculated, it was used to determine the influence of broadband noises with the weighting function, Eq. (30):

$$w_3(\Delta SPL_i) = \Big(1 - e^{-(\frac{\Delta SPL_i}{15})}\Big)^{0.29} \tag{30}$$

The weighting function for the frequency was defined with Eq. (31):

$$w_2(f_i) = \left[\sqrt{1 + 0.2 \cdot \Big(\frac{f_i}{700} + \frac{700}{f_i}\Big)^2}\right]^{-0.29} \tag{31}$$

Finally the weighting for the effect of bandwidth was calculated with Eq. (32).

$$w_1(\Delta z_i) = \frac{0.13}{0.13 + \Delta z_i} \tag{32}$$

In this formula, Δz_i was assumed to be the change of z from the beginning of the tonal component to the end of the tonal component. Afterwards, these weighted functions were combined in an overall tonal weighting function, Eq. (33):

$$w_T = \sqrt{\sum_{i=1}^{n}\left[w_1 \cdot (\Delta z_i)^{1/0.29} \cdot w_2(f_i)^{1/0.29} \cdot w_3 \cdot (\Delta SPL_i)^{1/0.29}\right]^2} \tag{33}$$

This was combined with the loudness weighting function w_{Gr}, which related the loudness of a spectrum without tones to the overall loudness of a spectrum, in Eq. (34):

$$w_{Gr} = 1 - \frac{N_{Gr}}{N} \tag{34}$$

Appendix C

The code writen to analyse the different aircrafts signals can be found at:

"https://drive.google.com/file/d/1oQ55RTKnN6JVgLyLaDuCZDHc3ueyWG3y/view?usp=sharing"

The entire zipfile content should be extracted and kept in the same folder. A manuel explaining the use of the program is included in the package.