# Aircraft Flyovers and Noise Annoyance: Which corrections? Which metrics?

E. Bessette, W. Dziarnowska, V. Guillet, R. Lampe, G. Onorato,

T. Rowntree, M. Saez Ortuno, Y. Uma Rucita, and L. den Ridder

*Faculty of Aerospace Engineering, Delft University of Technology, Delft, Zuid-Holland, 2629 HS, Netherlands*

**This study aims at understanding how to process raw sound pressure data, acquired from recording airplane noises, such that clear and accurate metrics that can quantify annoyance are achieved. Many attempts have been done by researchers to perform this. However, each effort has different approaches and its own errors. Three articles are used as the main literature, and additional papers are referenced to cover the knowledge gap. The raw data must first be corrected for doppler effect, geometric spreading, atmospheric variability, and geometric spreading. The refined data must then be represented in a useful way thus the metrics are implemented. The first main metric is loudness. To substantiate loudness, the Sound Pressure Level (SPL) must first be obtained which will then be corrected to perceived loudness using the noy table. Moreover, the adjustment for the duration of the sound is applied. The second notable metric is sharpness. This metric only takes into account the high frequency noises. Thirdly, tonality is another consequential metric. Scaling tonality can be most correctly done with the Aures tonality method. The last metric, psychoacoustic annoyance is essentially an integration of the previous metrics. However, it is more complicated to be visualised as it takes into account the subjectiveness of human perception. It is concluded after processing the data with the corrections and metrics, an annoyance ranking can be made. A program will be developed for this.**

## Nomenclature

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| $f'$ | Observed frequency, Hz |
| $f$ | Source frequency, Hz |
| $c$ | Speed of sound, m/s |
| $\frac{dr}{dt}$ | Rate of change of distance, m/s |
| $M$ | Mach number |
| $\theta$ | Angle between source direction of motion and the observer, deg |

## I. Introduction

If the noise emanating from an aircraft flyover were to be recorded from a ground-fixed microphone and analysed directly, the results would not accurately transcribe reality. Data correction and treatment is required to properly assess the noise annoyance. In order to tackle this issue of turning raw data into profitable quantities, three articles were studied, namely *Assessment of Noise Level Variations of Aircraft Flyovers Using Acoustic Arrays* [1], *Assessment of Noise Variability of Landing Aircraft Using Phased Microphone Array* [2], and *Model-based synthesis of aircraft noise to quantify human perception of sound quality and annoyance* [3]. Article 1 [1] presents two experiments that focus on "variability in noise levels for flyovers of the same aircraft type."[1]. An acoustic camera was used, to conclude that "variations in engine setting explain over 70% of the observed total noise level variation" [1]. Article 2 [2] addresses the same issue as Article 1, emphasizing the fact that "these variations are not properly considered by the current models, such as the Noise-Power-Distance tables." 2. To this end, a 32 microphone phased array was used, along with the application of "functional beamforming" [2]. However, while greatly focusing on the correction of data, both of these articles did not consider certain metrics such as loudness, sharpness, or tonality. Finally, Article 3 [3] presents a synthesizing method that works in parallel with executing jury tests, to evaluate aircraft noise as perceived on the ground. The article highlights the "quick and economic evaluation" [3] of an aircraft's noise available to designers, and affirms that "the developed synthesis method is adequate for all jet engine aircraft in the fleet of passenger aircraft ann

2005." [3], thus making it not valuable for aircraft manufactured in any other year than 2005.

The three articles present many useful techniques but at the same time, they neglect certain relevant aspects of those experiments. These sources thus present a knowledge gap that ought to be filled. The purpose of this paper is to evaluate where this gap lies today, and how far experiments were taken to consider the subject of aircraft flyovers noise annoyance.

To approach this problem, section II will present information regarding data corrections, such as the Doppler effect, geometric spreading, as well as the atmospheric spreading and background noise. Following this, additional theory will be given in section III concerning several metrics such as psychoacoustic annoyance, loudness, sharpness, tonality, and others.

## II. Data Corrections

### A. Doppler effect

In Article 1 de-dopplerization was dealt using the following equation:

$$\frac{f'}{f} = \frac{c}{c + dr/dt}, \tag{1}$$

where $f'$ is referred as the observed frequency while $f$ is the frequency of the source, $dr/dt$ is the rate of change of the distance between source and receiver and $c$ is the speed of sound. If all the data from Eq.(1) is known, the observed frequency can be converted into the real frequency. Finally, the observed frequency is plotted against the time.

In Article 2 the Doppler effect is corrected using the equation:

$$\frac{f'}{f} = \frac{1}{1 - M \cdot cos(\theta)} \tag{2}$$

where $f'$ and $f$ were described in the previous method, $M$ is the Mach number vector and $\theta$ is the angle between the source and the observer. If all the values are know, the corrected frequency $f$ can be calculated.

In Article 3 no information about the trajectory of flight was available and hence Eq.(1) cannot be used directly to calculate the Doppler shift. The description of the approach the researchers developed is briefly described hereunder.

The article describes the frequency vs. time behaviour of a single tonal component by indicating some points of the component in the time-frequency spectrum. The time-frequency behaviour of this tonal component is derived from the indicated points by performing a low-pass interpolation. The obtained curve is then corrected at each discrete time step by searching for higher amplitudes at spectral lines in the neighbourhood of the original curve in the time-frequency spectrum. In case higher amplitudes are found, the frequency is corrected (the frequency of the spectral line with the highest amplitude is retained). The speed of the aircraft relative to the observer in function of time is derived from this corrected curve by using the Doppler Eq.(1). After marking the behaviour of this first tonal component in the time-frequency spectrum, the user marks one more point for each additional visible tonal component in the spectrum. Then, together with the inferred speed of the aircraft towards the observer, the frequency vs. time behaviour of all other tonal components are calculated.

Article 1 and Article 2 are relevant for the research because they refer to flight paths and velocities of the landing airplanes. The articles use the same principle to calculate the frequency at the source even if they use different variables in the equation. The Doppler effect can be well modeled with the proposed method, it gives a high accuracy in the experiment and therefore will be used in the final research. Nevertheless, the method proposed in Article 3 is also considered highly relevant as it will provide the future research with an alternative approach to the de-dopplerization, useful to double check the result obtained with the former method.

### B. Geometric spreading

Among the phenomena playing a critical role in sound analysis, geometric spreading requires special attention. The "inverse square law" (geometric spreading) states that the intensity is inversely proportional to the square of the distance. As the sound moves away from the source, the area covered by the sound increases with the square of the distance, resulting in the final recording needing corrections for proper representation of the noise at the source. To successfully analyze sound levels, the recorded sound needs to be retraced back to the source, which can be achieved through a number of different methods.

The objective of the research in Article 1 is to analyse the sound pressure level and relate this to different aircraft configurations. To this end, the geometrical spreading must be applied. This phenomenon is thus discussed presenting the consequences of applying this correction when making a source map.

Article 2 covers the topic of geometrical spreading as well, introducing a simpler method to take into account this correction. It is thus considered a better source of information. The article gives a direct method for correcting the propagation effects. The paper has the advantage of proposing a fairly straightforward method for accounting for the phenomena, with the downside of making a number of assumptions, including non-uniform temperature effects on sound speed and moving medium (which have been neglected). These simplifications however may make the model less representative of reality.

Article 2 contains several references discussing a more detailed procedure of correcting geometrical spreading. From these sources, it was found that geometrical spreading can also be modeled through different advanced methods, including the Fast Field Program (FFP), Parabolic Equation (PE) method and Ray Tracing (RT). This allows to account for a number of other related phenomena but requires a fair bit of extra calculation and computations.

### C. Atmospheric variability

When examining the variability of noise levels in aircraft flyovers, the changes in atmospheric conditions during the measurements are an area of interest. In essence, one would like to get an idea ~~as to~~ how much these changes influence the recorded noise level.

In Article 1, a separate full scale test was conducted of which the outcome is best summarised with the following: "The variability in the received sound pressure levels, observed during more than one year, was less than 2 dB and showed no correlation with the weather parameters (like the mean and standard deviation of the windspeed) measured simultaneously" [1]. Even though the test only proved atmospheric variability is negligible, the fact that this first hand experiment was conducted is an advantage of Article 1, especially in comparison with the other articles which simply omit this topic. Based on the articles, it seems reasonable to assume that the variability in atmospheric conditions is not a dominant factor when researching the total variability in noise levels of aircraft flyovers.

### D. Background noise

A final correction that is sometimes performed is to take into account the effect of the background noise that is always present during the measurements. Looking at the the three main articles for reference, two approaches with respect to this problem can be distinguished. In Article 1 and Article 3 the data is not corrected for background noise, likely because the effect is found to be negligible. In Article 2, a threshold of 30 dB is set. Every recorded sound below this 30 dB is assumed to be due to the background noise present and is not represented in any of the final data.

## III. Metrics Theory

Different types of sound attributes are responsible for the annoyance felt by a human ear during an aircraft fly-over or landing. In terms of annoyance, loudness is considered to be the strongest one, followed by other ones such as sharpness, roughness and fluctuation strength [4]. It is important to note that the three key articles that were chosen ~~did not provide enough information on most of the metrics,~~ which lead the team to research further about them. The metrics theory can thus be considered as a knowledge gap that our team could close.

### A. Loudness and its Components

The current techniques of measuring sound annoyance are a result of years of studies and constant applications of corrections and analyzing more factors. The metrics that were used in the past to assess the sound noisiness are currently merely components of the newly defined metrics.

One of the oldest ways to measure the perceived noisiness of aircrafts by observers on the ground is the Effective Perceived Noise Level (EPNL), a scale developed by K.D. Kryter in 1959. This metric is not the most accurate method of assessing the no~~isiness~~ and currently, more advanced techniques are applied. Nevertheless, it is crucial to calculate the EPNL, as it can be later used as one of the factors affecting the sound volume as perceived by human brain, namely the Loudness. Obtaining this metric is a commonly known straightforward process described in many papers, such as "Aircraft Noise Evaluation" [5]. The first step is obtaining the Sound Pressure Level (SPL), a metric that uses a logarithmic scale representing the ratio of the sound pressure and a reference pressure. Then, each measured one-third octave band SPL can be converted into perceived noisiness by means of a noy table. Subsequently, these values of noys are combined and further corrected for the irregularities in the spectrum of the sound (tones). Finally, the duration of the sound should be implemented in the analysis which finally leads to obtaining the EPNL.

Another metric found is the A-weighted Sound Pressure Level, also referred to as dBA. This metric is developed from the fact that the human ear is less responsive to frequencies below 1000 Hz and above 6000 Hz. The metric reduces the amount of decibels at lower frequencies according to a curve, such that the higher frequencies are weighted higher. The curve is slightly different at different levels of loudness, such that the correction is smaller at higher levels of loudness.

Besides the A-weighted SPL, the C-weighted SPL also has been used to measure noise around certain airports, especially to focus on low frequency noise made by aircraft during take-off and landing. According to [6], this metric is used to assess ~~the noise~~ annoyance when the sound is dominated by frequencies below 250 Hz. The C-weighted SPL does not reduce the noise made by low frequencies as much as the A-weighted SPL, and rather slightly reduces the noise above 4000 Hz.

All of the previous discussion is a pursuit to quantify the loudness. From Article [7], loudness is understood to be the sensation of sound volume as perceived by humans. Loudness is a subjective perception thus, it is not to be confused with physical value such as the previously mentioned Sound Pressure Level (SPL), it is only related to it. Loudness is visualised in a linear scale and it is represented by a unit called "sone". This measure of loudness is based on three different aspects which are SPL, the frequency, and duration of the sound. Frequency plays a big role in determining how the loudness is subjectively perceived which is further discussed in subsection C.

### B. Sharpness and Tonality

Concerning the effect of sharpness, only Article 3 mentions it, describing a synthesis method to take it into account, as well as the influence of roughness, frequency and loudness of tonal components. This method works with the recorded sound fragment and results in a synthesized aircraft noise which can then be used to draw conclusions about the original analyzed data. More research was done on this phenomenon, and it was found that Sharpness is considered to be the fourth relevant sound quality attribute for aircraft noise [6], due to the fact that it only represents the noise of high frequency present in any sound sample.

As for the influence of tonality, again only Article 3 refers to it and explains its importance. For this article, a research was conducted in which 21 people compared sound fragments on how annoying they were. Tonal components with high frequencies were perceived to be more annoying and according to Article 3, "Loud tonal components with frequencies above 4000 Hz are extremely annoying." [3]. The source establishes that tonality cannot be ignored for measuring annoyance. However, the article does not mention a scale or a method to determine how annoying ~~the~~ tonality is. Aures tonality method is the closest method to the real annoyance level [6]. He reasoned that tonality should depend on the prominence of tonal components, which is already implemented in the conventional metrics, but also the frequency and bandwidth of tones which were never considered before.

### C. Psychoacoustic Annoyance

"Psychoacoustic annoyance is the science of the relationship between physical quantities of the sound and subjective hearing impressions" [8]. It is the result of a combination of different physical parameters (including Sound Pressure Levels, frequency, and modulation depth) and psychoacoustic parameters, which include roughness, fluctuation strength, loudness, and tonality. Using this metric enables to predict perceived noise annoyance effectively. The very high subjectivity of sound perception should however not be forgotten, making studies in this field very open ended and subject to constant possible improvement.

None of the three articles investigated here mention the application of these parameters in their studies. This could be explained by the fact that those psychoacoustic parameters are among the most complex metrics to be determined and employed effectively. Applying them in the quantification of sound annoyance would allow for a more advanced analysis, focusing more on the "human perception" side of the equation.

## IV. Conclusion

The main purpose of this report was to evaluate where the knowledge gap lies today, and how far experiments were taken to consider the subject of aircraft flyovers noise annoyance. After the analysis of the three main articles the initial question of this report can be solved. A combination of the three articles will be used for the corrections in section II. No knowledge gap exist around this topic and thus Article 1 and Article 3 will be used for the Doppler effect and Article 2 will be used for geometric spreading. Atmospheric variability and background noise will not be corrected in the future research, since both Article 1 and Article 2 state that it is negligible.

The metrics are a whole different topic. It is clear that a knowledge gap exists in the three inspected articles. This gap is related to how the information is treated after the correction methods are applied. Following the topic of the report, the challenge is to investigate the annoyance of the engines related to humans. This must be done by investigating certain parameters of the sound produced by the airplanes. None of the articles mentioned these metrics. Thus, the knowledge gap was closed using Book [6], Book [5] and Book [4] and is represented in section III.

Today's world is missing a system to classify the annoyance of the aircraft. For this, a program will be developed that can go from the raw data of a simple microphone to a ranking of annoyance.

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