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Noise attenuation directly under the flight path in varying atmospheric conditions

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ABSTRACT

When measuring aircraft noise, variations of up to 12 dB occur for identical aircraft types flying the same procedure directly over the same microphone position. It is assumed that these variations are the combined effect of variations at the source and in the atmospheric propagation, both not accounted for in standard noise calculations. This paper presents experimental results of the variation in noise levels due to a varying atmosphere. In 2010, an experiment was started to study the atmospheric effects on vertical propagation. A sound source was installed up in a weather-measurement-tower. This setup simultaneously recorded the atmospheric conditions and the variation in sound attenuation over an extended period of time. More than a year later, all measurement results were collected and multiple linear regression analysis was applied with the intention of deriving weather dependent correction factors to improve aircraft noise predictions methods. However, the result of the regression analysis shows that the obtained relations are weak and a significant part of the excess transmission loss remains unexplained. The main question, which part of the 12 dB can be attributed to variations in atmospheric conditions, could therefore not be answered.

Keywords: Noise attenuation, propagation, experiment

1. INTRODUCTION

Aircraft operations in the Netherlands are regulated to minimize noise impact. Regulations are based on a standardised noise prediction method, mostly comparable to methods described in well-known methods [1, 2]. As a result of the assumptions made in such a methods, discrepancies occur when comparing measurements with predictions. A variation as large as 12 dB may occur directly under the flight path, as depicted in Figure 1.

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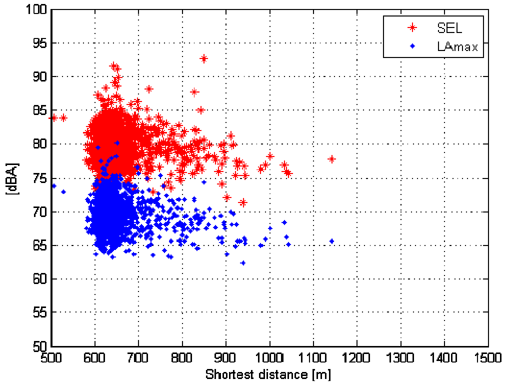

Figure 1 Measured sound levels of Boeing 737-800 aircraft as they pass directly over a noise measuring station near Schiphol airport throughout a period of four months.

A standardized method would predict a consistent sound level for all identical aircraft flying the same procedure. The fact that there is variation for the same aircraft type passing at a similar distance in Figure 1, indicates that the prediction model is lacking fidelity.

Aircraft noise policies in European states are typically based on the L_{DEN} (and L_{NIGHT} metric). This particular metric sums the sound energy (SEL) throughout the year including a penalty for a day, evening or night event. Consequently, directly underneath the flight path, where sound levels are high, there is a large contribution to the L_{DEN}.

There are two factors accountable for the measured variation. First, each aircraft may fly a slightly different trajectory and/or use a different power setting. Secondly, as the sound waves propagate through the atmosphere, several effects (absorption, refraction, diffraction and turbulence) affect the measured sound level on the ground. Hence, the measured variation is herewith either caused by a varying source or varying atmospheric characteristics.

It is well established that propagation effects may have a significant influence on sound levels. These effects are usually studied in literature for ground-to-ground propagation and long-range propagation [3]. Refractive effects cannot be ignored in these kinds of shallow propagation angles. In this case directly under the flight path, air-to-ground propagation at high elevation angles and a short-range is considered. These are conditions where refractive effects are small. To pin point whether the variation is caused by source or propagation characteristics, an experiment was started in 2010. The goal of the experiment is to measure and analyze vertical considered propagation losses in a varying atmosphere; therefore a dedicated set-up was designed and installed (see section 2). The analysis of the results ought to indicate the sole attribution due to varying atmospheric conditions.

First results [4] showed transmission loss variations in the order or 4 dB (accumulated for the entire frequency spectrum) over 103 meters of propagation. No clear causes of the variation or trends were found. Since then the experiment continued leading to more results and varying atmospheric conditions that were measured.

Currently, a statistical method is used to analyze the data set. This paper provides the obtained results using the statistical analysis.

2. METHODOLOGY

2.1 Experimental setup

At the meteorological weather tower in Cabauw (the Netherlands), a speaker is situated 100 meters above the ground. Every hour, except during night hours to limit sound exposures at neighboring premises, an acoustic signal of 15 seconds is emitted. The played signal is a white-noise of 100 dB in the frequency band of 250-4000 Hz. Five microphones are measuring the emitted signal at the ground while mounted flush on a 40 centimeter metal plate [5]. Accordingly, the effect of ground reflection on transmission loss is excluded. The ground based microphones are situated in different wind directions as shown in Figure 2.

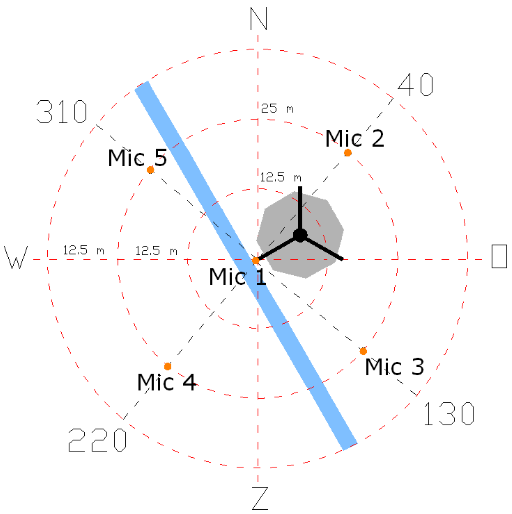

Figure 2 Top-view of the experimental setup in Cabauw. The meteorological tower is shown in black; the thick blue line is a ditch running through the Cabauw premises.

Due to speaker characteristics the signal does not have a perfectly flat spectrum. However, the Transmission Loss (TL) is established from the difference of the ground measured sound level and that of the emitted signal, measured in front of the speaker. The non-flat spectrum at emission is thus not reflected in the TL.

The weather tower is equipped to measure the atmospheric conditions. For instance, wind velocity and direction is recorded at different altitudes together with temperature. Humidity is measured at a ground based station. The atmospheric conditions during the sound measurement events have been recorded as well. The weather-measurement-tower continuously measures many parameters at different heights. The results are stored for later use, at relatively high sampling rates. This means that the actual conditions during each sound event are available from a database of atmospheric conditions.

The first two atmospheric parameters that were deemed to be relevant are temperature and relative humidity, as these two are the main drivers for atmospheric absorption. Wind is also expected to be a relevant aspect and is generally reported as a direction in combination with wind speed. Concerning this direction, for the analysis it has been assumed that not the actual azimuth, but the wind direction relative to the direction of sound propagation is relevant. To this end, all wind conditions have been recalculated and are reported as the parameter WR. This parameter is the cosine of the angle between the wind vector and propagation vector and is positive for downwind conditions. Finally, turbulence has been assumed relevant. The atmospheric parameter that has been used for the statistical analysis as a measure for turbulence is the standard deviation of the wind speed in the 10-minute period around the measurement event.

2.2 Analysis

The overall measurement period ranged to approximately 1 year. Table 1 shows the total data set used in this study.

Table 1 The data set used in this study

Seasons	Periods	Number of Valid data points
Autumn	01-Sep-10 to 30-Nov-10	605
Winter	01-Dec-10 to 28-Feb-11	231
Spring	01-Mar-11 to 31-May-11	989
Summer	01-Jun-11 to 31-Aug-11	565
		2390 (Total)

From Table 1 it becomes clear that the number of valid data points obtained in the winter season is relatively low compared to the other months. This is due to the fact that on snowy days the data points have been removed. Since the measurement was remotely monitored throughout the year, there was a risk that snow was present on the ground plate or on the microphones. Therefore these data points were removed. Due to the long measurement period and varying conditions, some of the microphones became malfunctioned. As a result, only the data gathered by microphones 2,3 and 5 (see Figure 2) were used in the analysis.

The transmission loss is analyzed for different frequency bands with center frequencies ranging from 500 Hz to 3000 Hz. Below 500 Hz, the Signal to Noise Ratio (SNR) deteriorated due to the presence of background noise. Due to the vicinity of neighboring communities and speaker characteristics, the maximum sound level at the source was limited. Consequently, for emitted sound with a frequency above 3000 Hz the atmospheric absorption became an important factor and the SNR deteriorated again.

To obtain a clear impression of the wind and turbulence effects, the influence of atmospheric absorption was removed [6]. Due to the varying humidity and temperature (to be shown later in Figure 3) the absorption varies between the data points. Besides the absorption effect, the effect of spherical spreading was removed as well. Therefore all the results presented further on in this study attribute to calculating an excess transmission loss.

With help of regression analysis, dependencies are searched for in the data set. The significance level (p) was calculated for each correlation coefficient. Data exhibiting value of p less than 0.05 were excluded from further analysis, as is common in statistical literature [7].

Simple linear regression fits a line through a set of points based on one independent variable. In [4] it was found that there is no clear trend directly obtainable. This is why the extension to Multiple Linear Regression (MLR) analysis is used. MLR allows determining the combined influence of the atmospheric variables rather than the effect of a single parameter. As is the case with simple linear regression analysis, MLR tries to fit a line through the data set. The line equation is given by Eq. (1) and follows [8]:

$$y = B_1 x_1 + B_2 x_2 + B_3 x_3 + B_4 , \qquad (1)$$

where the coefficients B_i of Eq. (1) form a linear relationship between the independent atmospheric variables (x_i) and the desired parameter (y), i.e. the transmission loss. The coefficients B are found by solving the system of equations in the least-square sense. When establishing these coefficients, it is possible that a constant deviation remains. This deviation is formed by the coefficient B_4 and is the variance in transmission loss that cannot be attributed to one of the atmospheric parameters through MLR.

3. RESULTS & DISCUSSION

3.1 Results

Figure 3 first summarizes the temperature and humidity conditions throughout the measurement period. For each season, the figure shows the mean temperature and relative humidity, as well as the standard deviation in both temperature and humidity.

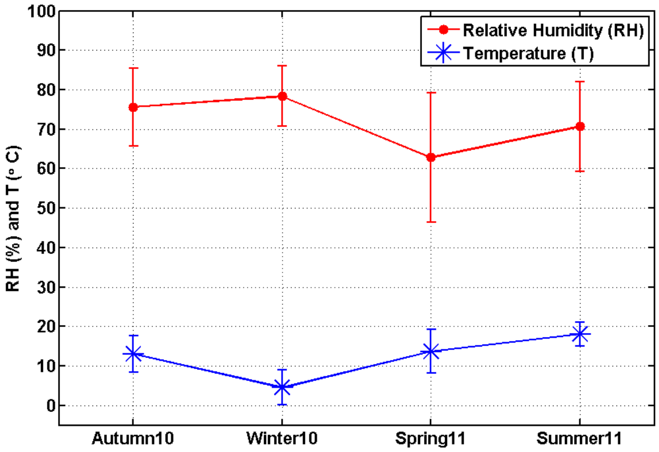

Figure 3 The variation in humidity and temperature recorded during the experiment.

It should be realized that the Dutch climate is an oceanic climate, which features a relatively narrow annual temperature range, and lacks a dry period. Results presented in this paper are not automatically valid for locations experiencing other conditions.

Figure 4 shows the wind and turbulence conditions throughout the measurement period. The wind direction shown in the figure (upwind/downwind) is the result for microphone 5 (310°).

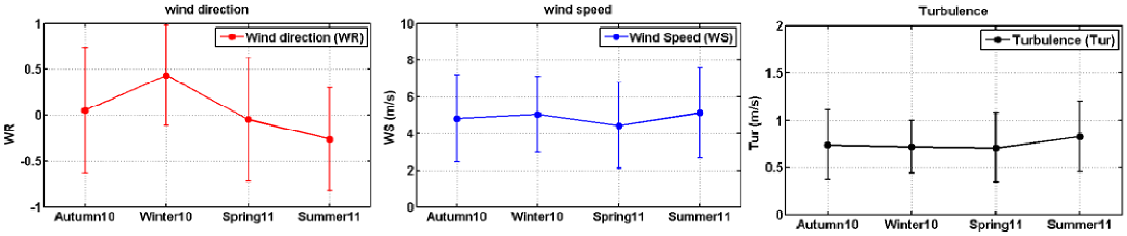

Figure 4 Variation in wind and turbulence characteristics.

The wind direction parameter WR varies throughout the seasons. For the microphone position shown here, downwind conditions are dominant in the winter season, while upwind conditions are more common during the summer season. For other microphone positions however, the results are different, due to the position of these microphones relative to the speaker. The wind speed and turbulence parameter show less variation throughout the different seasons.

Figure 5 shows two examples of the measured excess attenuation loss for microphone position two and five at the 1 kHz frequency band. As defined in section 2.2, the excess attenuation loss is the measured attenuation loss, corrected for spherical spreading and atmospheric absorption based on the temperature and humidity conditions at the time of the event.

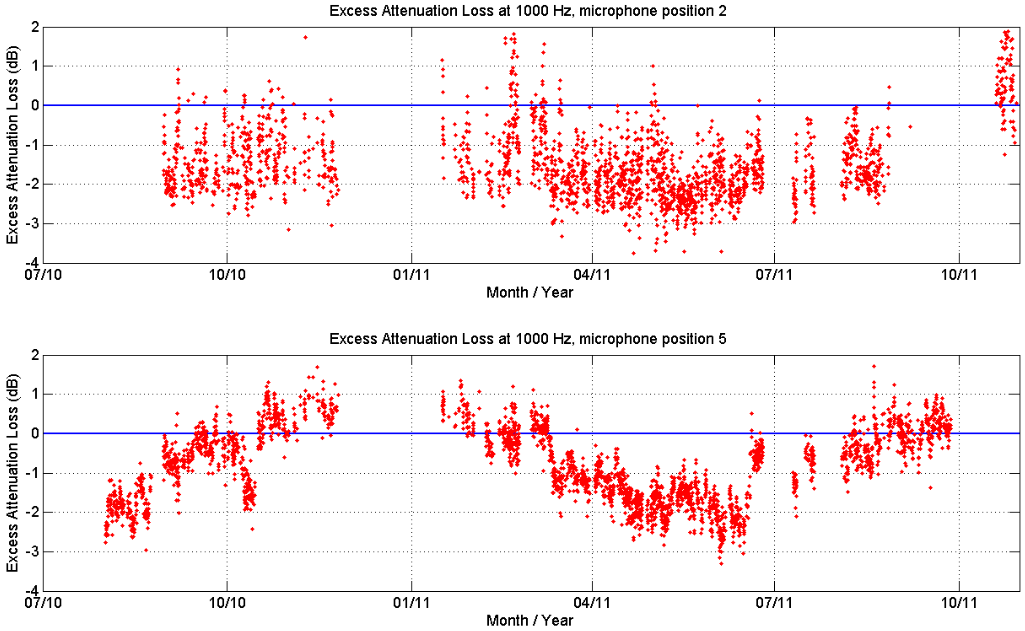

Figure 5: Examples of the measured attenuation loss for two microphone position at a single frequency band

For microphone position 5, a sinusoidal pattern can be distinguished in the lower subfigure of Figure 5. This pattern did not appear at other frequencies or microphones. More peculiar is the broad scatter (vertically) around the same time instant. This implies that a large variation is measured through a single day. The remainder of this section presents the results of the statistical analysis.

First, Figure 6 shows the correlation coefficients for the three independent atmospheric variables. All subfigures show the coefficients for all seasons and all one-third octave bands with center frequencies between 500 and 3150 Hz. Only results of adequately proven statically significance are shown, explaining the lack of data points and lines for particular frequency and season combinations.

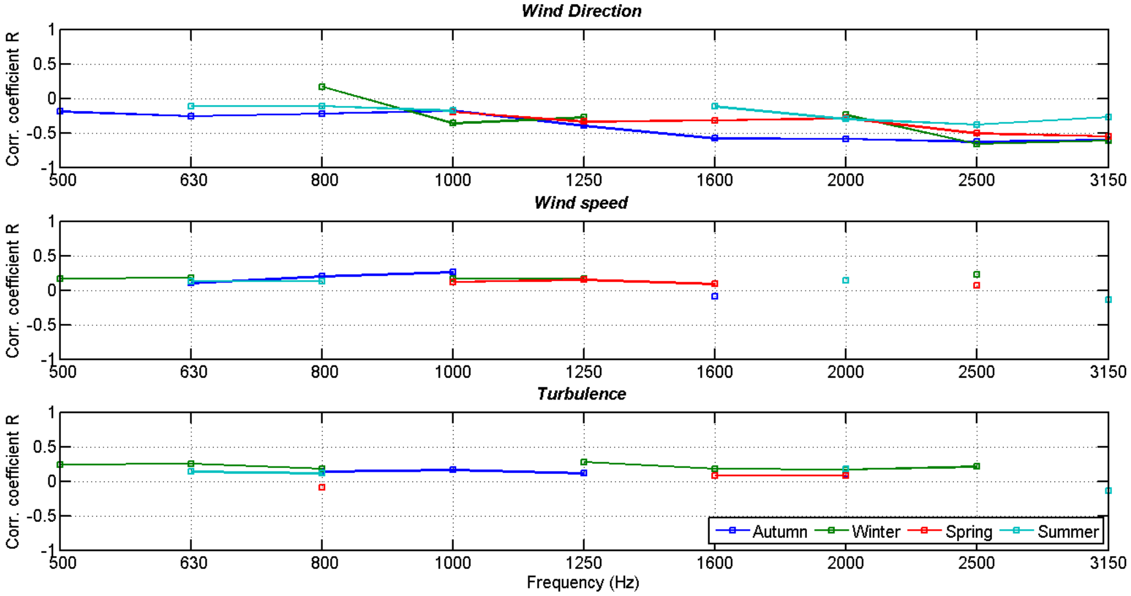

Figure 6: The calculated correlation coefficients.

Most of the correlation coefficients for the wind direction are significant, and especially for the higher frequencies, point towards a weak to moderate negative linear relation between the wind direction variable and the excess transmission loss. For wind speed and turbulence, more coefficients are missing from the figure due to the lack of statically significant results. The coefficient values that are shown in the figure indicate a weak, generally positive correlation for both variables.

Figure 7 presents the regression coefficients B1 to B4 of equation 1, obtained with the multiple linear regression analysis.

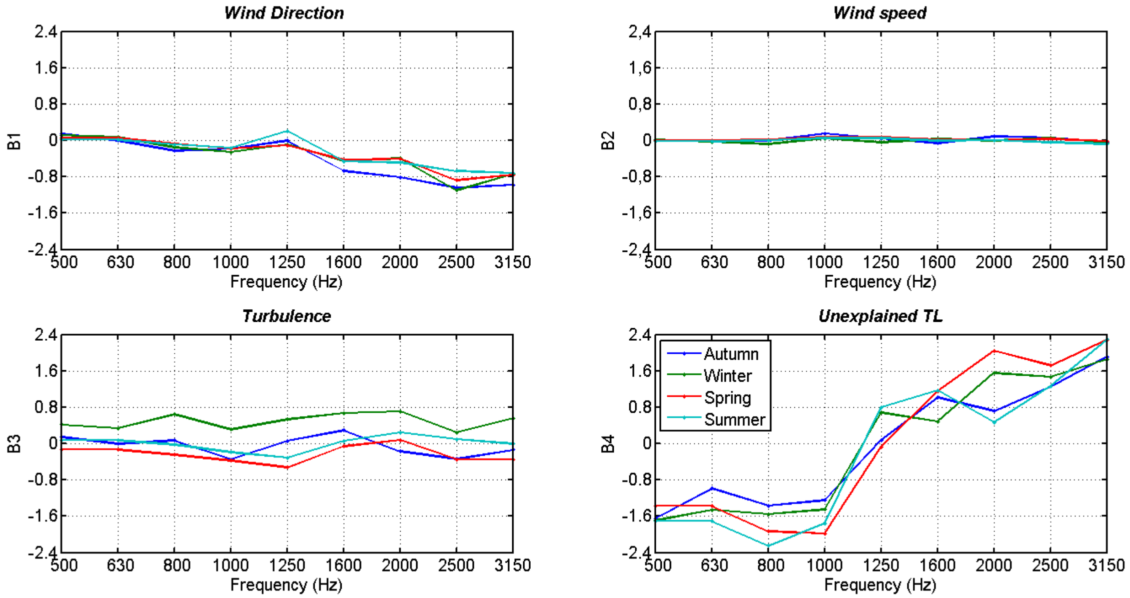

Figure 7: Resulting regression coefficients from the MLR analysis.

Based on the value of regression coefficient B1, the influence of the wind direction parameter for the lowest frequencies is negligible. For the higher frequencies however, the coefficients are clearly non-zero. Given the definition of parameter WR, the results shows that for downwind conditions the excess transmission loss decreases. Although the wind direction variable is of influence, the wind speed variable on the other does not seem to affect the transmission loss, as the value of coefficient B2 is near zero for all frequency bands and season.

Coefficient B3, used to model the influence of turbulence does not show a consistent trend. The regression coefficients are both positive and negative, seem to vary randomly with frequency and the results obtained for the winter season also appear to be inconsistent with the other seasons. Finally, the constant term B4 of equation 1 models the remaining or unexplained excess transmission loss that cannot be related to the three independent variables. For the lower frequencies, the unexplained transmission loss is negative, while for the higher frequencies, it is positive. This effect is fairly consistent over the different seasons.

3.2 Discussion

The results in the previous section show that the assumed multi-linear relation between the chosen weather parameters (wind speed, wind direction and/or turbulence) and the excess TL is not very good. The correlation analysis indicates that the assumed relations are generally weak. The regression analysis does point towards an effect of wind direction for higher frequencies, but the unexplained TL is far more dominant.

Based on these observations, two main possibilities have been identified:

- The statistical analysis can be improved
- The measured TL's have been influenced by other factors

With respect to the statistical analysis, there are several directions for further improvement. First of all, the chosen parameterisation could be re-evaluated. Currently, temperature and humidity have not been selected as independent atmospheric parameters, based on the assumption that their influence on excess TL has been removed by correcting for the actual atmospheric absorption. However, these two parameters could be included to test for any residual effects. A second suggestion is to use a different parameter to account for turbulence, because the current parameter – the standard deviation of a 10 minutes period – might be too coarse. Finally it should also be considered a possibility that the effects are highly non-linear and cannot be modelled using a linear model.

The measurement data might have been influenced by other factors. One concern is that the length of grass growing around ground plates might have had an effect. Another possibility is that dew or other forms of moist on the microphone diaphragm might have influenced some of the measurements. A third thought is that background noise could have been an issue. Although all events have been scrutinized by comparing the ambient conditions around the noise event with the levels during the event itself, this check was performed on the A-weighted equivalent levels only.

The question which part of the 12 dB difference[2] shown in Figure 1 can be explained by varying atmospheric properties remains to be answered. To answer this question, the results would also have to be scaled from the 100 meters of the experiment to the 600 meters of the aircraft flyover. A method to perform this scaling has been identified and tested [9]. However, due to the poor reliability of the obtained regression model, this analysis has not been completed and is not shown here.

To fully understand the scatter in Figure 1 it is recommended to also study the influence of the source by correlating aircraft settings with the noise events. This alternative approach is however also not easy to undertake as research establishments and universities in general do have access to real and actual operational aircraft settings data.

4. CONCLUSIONS

A sound source was installed 100 meters above the ground in a weather-measurement-tower. This setup simultaneously recorded the atmospheric conditions and the variation in sound attenuation over an extended period of time. After all results had been obtained, multi-linear regression analysis was applied with the intention of deriving weather dependent correction factors to improve aircraft noise predictions methods.

The results of the regression analysis show that the correlation coefficients for the regression model are relatively low, pointing towards weak correlation. Furthermore, a significant part of the excess transmission loss remains unexplained. Based on these results, the main research question could not be answered with sufficient confidence.

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[2] Please note that the 12 dB is including the effects of atmospheric absorption, while the regression model presented in this paper models the variation excluding the effect of atmospheric absorption.

REFERENCES

[1] Integrated Noise Model (INM) Version 7.0 Technical Manual, FAA-AEE-08-01, January 2008

[2] Report on Standard Method of Computing Noise Contours around Civil Airports, ECAC.CEAC Doc.29, 3rd Edition, Volume I & II, December 2005

[3] K. Attenborough, K. M. Li, and K. Horoshenkov, Predicting outdoor sound, Taylor & Francis, 2007

[4] D. Bergmans, M. Arntzen, W. Lammen, “Noise attenuation directly under the flight path”, in proceedings of Internoise 2011, September 4-7, Osaka, Japan.

[5] International Civil Aviation Organisation (ICAO), International standards and recommended practices, *“Environmental protection” Annex 16*, volume 1 “Aircraft noise”, 3rd edition July 1993

[6] SAE Standard Values of Atmospheric Absorption as a Function of Temperature and Humidity, SAE-ARP-866A, March 1975

[7] F. J .Manly, Multivariate Statistical Methods, 1944 Chapman and Hall.

[8] D.G. Simons, M. Snellen, M.A. Ainslie, A Multivariate Correlate analysis of High-frequency bottom backvariationing strength measurements with geotechnical parameters, Ocean Engineering, Volume 32, Issue 3, 2007, Pages 640-650.

[9] R. Deloach, “On the excess attenuation of sound in the atmosphere”, NASA Langley Research center, Hamption, VA USA, March 1975