Determining an empirical emission model for the auralization of jet aircraft

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Summary
Aircraft noise is a major issue in urban areas and is one of the research topics within the FP7 SONORUS project. Current methods for determining the impact of aircraft noise on annoyance and sleep disturbance are based on energetic quantities neglecting the dynamic character of the sound. To obtain a more complete representation of annoyance, it would be helpful to predict the audible aircraft sound and determine the impact of the aircraft sound on people. In a related project at Empa, sonAIR, recordings were made of aircraft taking off and landing. These recordings were made at several positions and with several microphones simultaneously. Combined with cockpit data, flight path information and an inverse sound propagation model, this gives the possibility to determine the emission as function of aircraft conditions and observer angle. An inverse sound propagation model is used to estimate the emission in the time-domain. The obtained signal corresponds to the immission of a microphone flying along with the aircraft and rotating about it. The time-domain approach allows extracting narrowband information like tones and time-dependent variations like modulations.

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1. Introduction

In order to investigate annoyance and sleep disturbance due to aircraft noise, an auralization tool is in development [3]. An auralization propagation model is in development that takes into account spherical spreading, the Doppler shift, atmospheric attenuation, reflections and also amplitude and phase modulations due to turbulence [4]. The current emphasis is on the development of an empirical emission model that describes both broadband noise and tones separately.

For the sonAIR project a (semi-)empirical emission model for noise prediction is being developed to replace the current FLULA2 emission model [6]. The emission model will produce 1/3-octave band levels. Calculation from source to receiver is also done in 1/3-octave bands using the sonX propagation model [7].

Jet aircraft noise consists of broadband noise combined with tones. These tones may affect annoyance and sleep disturbance and should be included in the auralisations.

This requires determining the tones and its (time-dependent) features, like the actual frequency, bandwidth and power. After these parameters have been determined, the tones should be subtracted from the signal. The remainder will be analysed in fractional octaves and eventually considered in the model as noise.

As a first step an inverse propagation model was developed that allows calculating back to the source in the time-domain. The inverse propagation model is based on the auralization propagation model and allows compensating for spherical spreading, Doppler shift and atmospheric attenuation.

In this paper we will have a focus on the inverse propagation model and discuss the influence of the ground reflection on uncertainties in the eventual model.

2. Measurements

In September 2014 aircraft noise recordings were made at several sites nearby the Zürich Kloten Airport [8]. During this period 1800 landings and 900 takeoffs were recorded. At any given time at least 7 microphones were used, each situated at a height of 4 meters and regularly synchronized using GPS time. The microphones' positioning was optimized in such a way that optimal directional information can be obtained.

Aircraft positional information was obtained by using an optical system consisting of two cameras capable of determining velocity and position. Furthermore weather information was available.

3. Inverse propagation model

The inverse propagation model is based on the propagation model that is used in the auralization tool and undoes the intensity loss due to geometrical spreading, as well as the delay that causes the Doppler shift. Furthermore, the inverse propagation model corrects for atmospheric attenuation. One effect the inverse propagation model cannot undo is the ground effect. Several implications of the ground effect can be found in the discussion.

3.1. Geometrical spreading

The first step in the inverse propagation model is to undo the intensity loss due to geometrical spreading. This is done by scaling the amplitude of the samples according to

$$p_{reverted} = p_{recording} \frac{r_{recording}}{r_{reverted}} \quad (1)$$

For $r_{reverted}$ a distance of 1 meter is used. The assumption is made the source can be considered a point. For large Helmholtz numbers the error of this assumption is negligible. For small Helmholtz numbers, e.g. in case of a low fly-over, the aircraft should be considered an extended source. In this case interferences between emission of the different parts of the aircraft may play a role.

3.2. Atmospheric attenuation

The second step is to undo the atmospheric attenuation. The attenuation coefficient for pure tones α is calculated according to ISO 9613-1 [1] in the frequency domain. This attenuation, corresponding to a (single-sided) power spectrum in decibels, is converted to a double-sided amplitude spectrum using

$$a_\alpha[k] = 10^{+d\alpha}, \quad 0 \leq k \leq N/2 \quad (2)$$

$$a_\alpha[-k] = a_\alpha[k], \quad 1 \leq k \leq N/2 - 1 \quad (3)$$

where M is the amount of desired filter taps, k the block index of discrete frequency f_k and d the source-receiver distance. Note also the plus sign; in case of an auralization this sign would be negative but now we're interested in an amplification. An impulse response is obtained by taking the IFFT of M blocks. The small imaginary parts are discarded by taking the real part. The filter is then made causal by rotating the impulse response with $M/2$ samples. A rectangular window was used.

The attenuation is range-dependent and because of the aircraft movement the range varies with time. Within one recording there is a maximum and minimum range. An N amount of impulse responses are determined for an N amount of equispaced ranges.

The attenuation is applied by performing a convolution between the impulse responses and the input signal. The convolution is done in a rather naive way by multiplying a Toeplitz matrix consisting of impulse responses with a vector representing the input signal. The impulse responses are stored as a sparse array to reduce memory consumption. No further operations were done regarding the impulse response transitions.

3.3. Propagation delay (Doppler shift)

The third and final step is to undo the propagation delay. The source is moving with respect to the receiver in such a way that the propagation delay is varying with time which results in a Doppler shift. Known are the flight trajectory, receiver position and the received signal. To undo the propagation delay the received samples need to be shifted in time to match with the retarded time. The retarded time is given by

$$t^{'} = t - \Delta s / c \quad (4)$$

where Δs is the path length and c the speed of sound. The speed of sound is calculated using

$$c = 343.2 \sqrt{\frac{273.15 + T}{293.15}} \quad (5)$$

where T is the actual temperature in degrees Celsius.

Since the signal is discrete and the delay is generally not an integer multiple of the sample time, an interpolation scheme is required. Earlier a linear interpolation scheme was used as described by [2]. Due to artifacts, Lanczos resampling is used now instead.

The Lanczos kernel is given by

$$L(z) = \begin{cases} \text{sinc}(z)\text{sinc}(z/a), & \text{if} -a < z < a \\ 0, & \text{otherwise} \end{cases} \quad (6)$$

where a is the size of the kernel. Consider now a signal with samples s_i for integer values of i where sample s_i corresponds to the sample at $t = i/f_s$. The value at retarded time t' is then given by

$$S(x) = \sum_{\lfloor x \rfloor - a + 1}^{\lfloor x \rfloor + a} s_i L(x - i) \quad (7)$$

where x is the sample at retarded time t'

$$x = -t' + i \quad (8)$$

The frequency shift depends on the change of propagation delay. Therefore, when source and receiver are relatively close to one another, the method is most sensitive to uncertainties in source position and speed of sound.

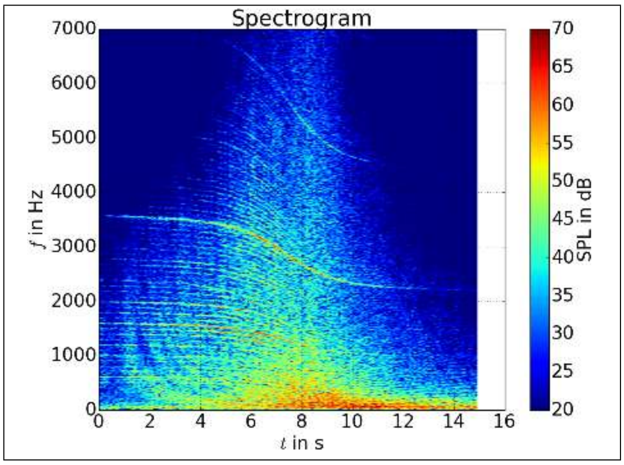

Figure 1. Spectrogram of the recording. Clearly visible are the Doppler shifted tones.

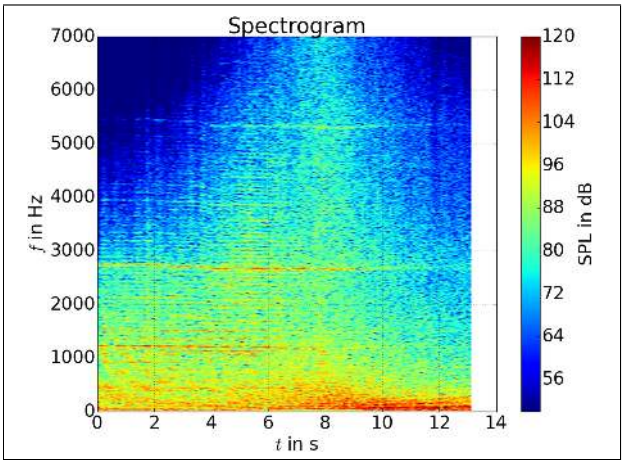

Figure 2. Spectrogram of the recording after applying the inverse propagation model. The frequency of the tones now corresponds to the emission frequency.

4. Results

The inverse propagation model is now exemplified by applying to a recording of an Airbus A320 takeoff. The sample rate of the recording was 44.1 kHz. For the propagation delay a Lanczos kernelsize of 10 was used. For the atmospheric attenuation 100 unique impulse responses were calculated, each consisting of 256 taps. Both the recording and the reverted signal are available online [5].

Figure 1 shows the spectrogram of the recording. Clearly visible are the tones and the Doppler shift. Less pronounced but still visible is the ground effect.

Figure 2 shows the spectrogram after the inverse propagation model has been applied. Note that the reverted signal is shorter than the original signal; to determine the emission at t' corresponding to the measured immission at t requires source position information at the retarded time t'. In the shown example the source position at those times was unavailable and therefore the signal was shortened.

Judging from the spectrogram, the Doppler shift seems to be removed. The tones are however not entirely straight in the spectrogram. Changes in thrust can cause fluctuations in the tones. In this case there seems to be a systematic error, possibly due to an offset in the aircraft position information. A propagation effect that remains clearly present is the ground effect.

Figure 3 shows the overall sound pressure level as function of time. Fluctuations, which are mostly due to interference, are clearly visible. Turbulence can also cause fluctuations but with this geometry and weather conditions these fluctuations are much smaller than the fluctuations due to interference. Emission fluctuations are possible but unlikely; the aircraft takes off with constant velocity and constant thrust.

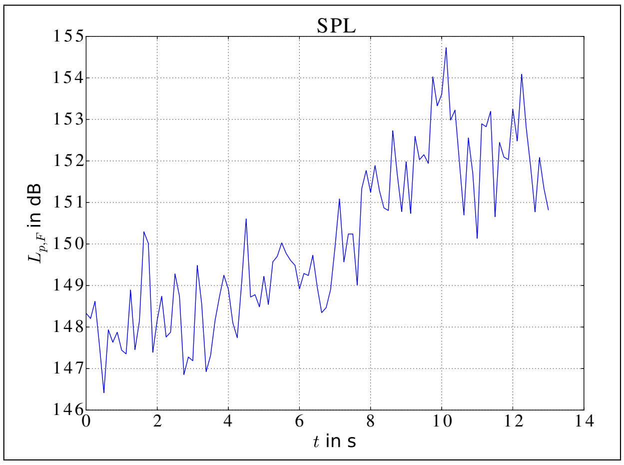

Figure 3. Sound pressure level as function of time after the inverse propagation model has been applied. Fast time weighting, no frequency weighting)

5. Discussion

The shown method makes it possible to undo several propagation effects however the result obtained still contains the contribution from the ground reflection. While auralizations should contain the ground reflection, it is unwelcome contribution for the analysis of the emission. The ground reflection has several implications, all of which might be prevented when a directional microphone would be used that would track the angle of refraction of the ground reflection and adjust its directivity pattern accordingly. Another possibility would be to place the microphone on the ground, but this results in other problems like shielding, making parts of the recordings unusable.

The interferences result in a spread of the sound pressure level and therefore in an inaccuracy of the model parameters that we aim to determine. Ignoring for a moment the time-varying phase difference between direct and reflected contribution, there is or would be an amplitude offset because of the reflection from the ground. One could predict the reflection coefficient and apply a frequency-dependent correction which, because of uncertainties, should probably be an amplitude-only correction.

Also, because the angle between mirror source and receiver is different from the angle between the real source and receiver there will be a difference in Doppler shift between the direct contribution and the ground reflection contribution. With the geometry considered this effect is small, resulting in a slightly wider peak.

6. CONCLUSIONS

An empirical emission model is being developed as part of an auralization tool. Because recordings were made at several positions simultaneously and since source position information is available it should be possible to determine the half-sphere directivity of the aircraft.

To obtain the features that will be used to determine the model parameters an inverse propagation model is used that allows calculating back to the source in time-domain, undoing several propagation effects. The ground effect however could not be undone using this method causing a spread in the features, which in effect will result in an uncertainty of the model parameters.

The next step is to implement a peak detection and tracking algorithm in order to detect and track the tonal components. That tool will then be combined with the in this paper described method to obtain features that can be used for a statistical analysis of the emission.

Acknowledgement

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References

[1] ISO 9613-1:1993 - Acoustics – Attenuation of sound during propagation outdoors – Part 1: Calculation of the absorption of sound by the atmosphere. 1993. URL: http://www.iso.org/iso/iso_catalogue/catalogue_tc/catalogue_detail.htm?csnumber=17426.

[2] Kurt Heutschi, Reto Pieren, Menno Müller, Madeleine Manyoky, Ulrike Wissen Hayek, and Kurt Eggenschwiler. Auralization of Wind Turbine Noise: Propagation Filtering and Vegetation Noise Synthesis. *Acta Acustica united with Acustica*, 100(1):13–24, January 2014. URL: http://openurl.ingenta.com/content/xref?genre=article&issn=1610-1928&volume=100&issue=1&spage=13, doi:10.3813/AAA.918682.

[3] Frederik Rietdijk. Auralization of aircraft noise in an urban environment, November 2014. URL: http://zenodo.org/record/12642, doi:10.5281/zenodo.12642.

[4] Frederik Rietdijk, Kurt Heutschi, and Jens Forssén. Modelling sound propagation in the presence of atmospheric turbulence for the auralization of aircraft noise. *The Journal of the Acoustical Society of America*, 136(4):2286–2286, October 2014. URL: http://scitation.aip.org/content/asa/journal/jasa/136/4/10.1121/1.4900268, doi:10.1121/1.4900268.

[5] Frederik Rietdijk, Kurt Heutschi, and Christoph Zellmann. Determining an empirical emission model for the auralization of jet aircraft. 2015. doi:10.5281/zenodo.15702.

[6] B. Schäffer, C. Zellmann, W. Krebs, S. Plüss, K. Eggenschwiler, R. Bütikofer, and J.M. Wunderli. Sound source data for aircraft noise calculations - State of the art and future challenges. In *Proceedings - European Conference on Noise Control*, pages 589–594, 2012. URL: http://www.scopus.com/inward/record.url?eid=2-s2.0-84865960623&partnerID=tZOtx3y1.

[7] J. M. Wunderli, R. Pieren, and K. Heutschi. The Swiss shooting sound calculation model sonARMS. *Noise Control Engineering Journal*, 60(3):224–235, 2012. URL: http://www.scopus.com/inward/record.url?eid=2-s2.0-84865976058&partnerID=tZOtx3y1.

[8] Christoph Zellmann, Jean Marc Wunderli, and Beat Schäffer. SonAIR - Data acquisition for a next generation aircraft noise simulation model. In *42nd International Congress and Exposition on Noise Control Engineering 2013, INTER-NOISE 2013: Noise Control for Quality of Life*, volume 1, pages 842–850. OAL-Osterreichischer Arbeitsring fur Larmbekampfung, 2013. URL: http://www.scopus.com/inward/record.url?eid=2-s2.0-84904458708&partnerID=tZOtx3y1.