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Optimal estimation of aircraft noise with four microphones in a spatial configuration

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By using all time shifts between the arrivals of the acoustic signal at the four microphones in a spatial configuration the source direction is obtained. The used correlation technique reduces significantly noise from other sources and the error in the estimated noise from the tracked aircraft. By taking into account a motion model, the history of the motion and the observed acoustic data a very robust sound monitor system is obtained. The sensitivity for other sources, like wind and rain noise, is greatly reduced - theoretically almost unlimited - in comparison with classical monitor systems. Four aircraft can be tracked simultaneously.
Another system capability is the estimation of the true flight path with a system error depending on the system configuration and the environmental conditions. Using this path information the soundscape can be calculated by inter- and extrapolation. The design goal of the system is truly met!

Introduction

For high precision aircraft noise monitoring a system has been developed with accurate tracking capabilities, based on correlation and extended Kalman optimization. Fig. 1 shows the spatial configuration of the four microphones of the system.

Fig. 1 Four microphones in a spatial configuration for aircraft noise monitoring.

Such configuration without any ambiguity about the sound arrival direction is for a monitoring system minimal.
The six time shifts between the sound arrivals at the four microphones are used to obtain the direction of the sound. This information is also used to obtain the strength of the aircraft noise without the contribution of noise from other sources. Besides the directly received sound also the strength of the ground reflected aircraft noise is obtained. Homo sapiens determines the direction (both angles) with two ears. However engineers could not duplicate the effectiveness of the nonlinear signal processing of nature. For that reason systems with 64 and 100 microphones in a spatial array on the order of 10 meters were proposed in the Netherlands. An other example is the EU SAFE Airport project with 512 microphones in a plane array. The latter with the intention to obtain besides direction also the range as a substitute system for a radar system.

History and a model for the moving source has been taken into account resulting in an extended Kalman optimization procedure. The accuracy is so high that passive ranging is possible for moving and stationary objects, with an error depending on distance, velocity and environmental parameters and the system configuration [1]. The sensitivity towards the environmental parameters will not be treated. However stationary sources are, like homo sapiens does, simply ignored as background noise. By using more systems the accuracy of the calculated flight path is increased even more. Also real flight data from local air traffic control authorities can be taken into account. With the flight path data and simultaneously taken spectra the local environment spectra are frequency-dependent interpolated from the measured spectra to other places and a soundscape is generated.

The acoustic signal processing

Fig. 2 shows the microphone system with a directional propagation vector for the acoustic pulse.

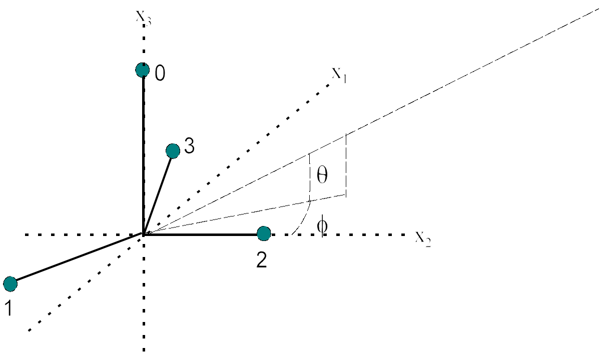

Fig. 2 The schematic microphone array.

The time delay τ_{a-b} between the acoustic pulse arrivals at microphones $\boldsymbol{a}$ and $\boldsymbol{b}$ is a function of angles θ and ϕ and is

$$\tau_{a-b} = \frac{\vec{l}_{a-b}\cdot(\vec{c}+\vec{v})}{c|(\vec{c}+\vec{v})| - \vec{v}\cdot(\vec{c}+\vec{v})} \qquad (1)$$

with base vector of microphone pair $\vec{l}_{a-b}$, the directional sound velocity $\vec{c} \equiv c\frac{\vec{x}}{|\vec{x}|}$ and the wind velocity vector $\vec{v}$.

The phase of the correlation signal of the $\boldsymbol{m}^{th}$ pair is

$$\varphi_m(k\Delta t) \equiv \varphi_{m,k} \qquad (2)$$

with Δt as the sampling interval and of the predicted phase function

$$\tilde{\varphi}_{m,k}(\omega,\phi,\theta) \equiv \omega[\tau_m(\phi,\theta)+k\Delta t] \qquad (3)$$

with ω as the momentary radial frequency.

To obtain the direction of the sound source the following cost function is defined and using *N+1* phase data of the 6 correlation signals

$$\chi^2 = \sum_{m=1}^{6}\sum_{k=-N/2}^{N/2}\left|\varphi_{m,k}-\tilde{\varphi}_{m,k}(\omega,\phi,\theta)\right|^2 W_{m,k} \qquad (4)$$

with $W_{m,k}$ the weight of the k^{th} phase datum of the m^{th} phase correlation signals with a value equal to the squared reciprocal of the timing error

$$\Delta t = \frac{1}{\omega}\sqrt{N(t)/S_{\max}} \qquad (5)$$

with $N(t)$ and S_{max} the noise and the signal in the correlation signal.

By minimizing Eq. (4) the best estimates for the direction of the source are obtained. Minimization of Eq. (4), by first linearizing Eq. (4), is known as the nonlinear least squares method. By adding the history - prior estimates - and a model the nonlinear least squares method is transformed into an extended Kalman filter procedure resulting in the estimated parameters with errors.
Up to 4 aircraft can be tracked simultaneously. The resolution depends on the dimension of the microphone array. In the same way the wind velocity vector is optimal estimated with a much larger time constant than for moving sound sources.
Noise from rain, wind and stationary sources is reduced considerably compared to classical signal processing.
Due to the effective signal processing the system has been implemented into a pc-104 cabinet, shown by Fig. 4.

Fig. 3 The signal processing PC-104 cabinet

The system is so accurate that the Doppler angular shift - equivalent to the Doppler frequency shift - due to the retardation by the finite sound velocity, is measurable. From this phenomenon the velocity, flight height and slope can be calculated with an error depending on the environmental circumstances. By combining two or more systems, taken into account the finite sound velocity and the wind vector the flight path from the time stamped parameters from these systems can be calculated with a much higher accuracy.
The soundscape is generated by using the estimated flight path and extrapolating/ interpolating the spectra at the monitoring sites to other positions of the soundscape.

Measurements

Fig. 4 shows the recording of two events, the parking of a car (green) and the passing over of a Boeing 747 (red). The latter appears in the western direction, passes over and disappears in the south eastern direction, see the compass card at the right in the figure.

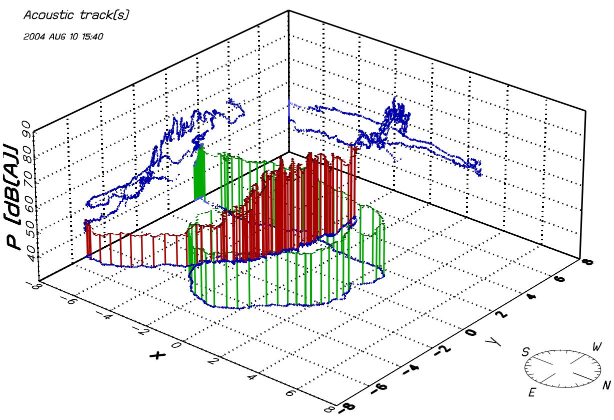

Fig. 4 Soundtracks recorded on a parking roof of a shopping mall in Castricum, 30 km north of Schiphol

The coordinates are relative to an height of 1. The detection is based on the position of the acoustic event relative to the horizon. By giving the event above the horizon the color red and below the horizon green, it is quite clear that red is an aircraft event and green local ground traffic event.
The widening of the gap between the vertical lines in the red soundtrack - these lines are drawn every second - is the Doppler effect. The effect is quite noticeable due to the large ratio of aircraft velocity and sound velocity ***v/c***.

The spectra of an aircraft passing over are shown by Fig. 5.

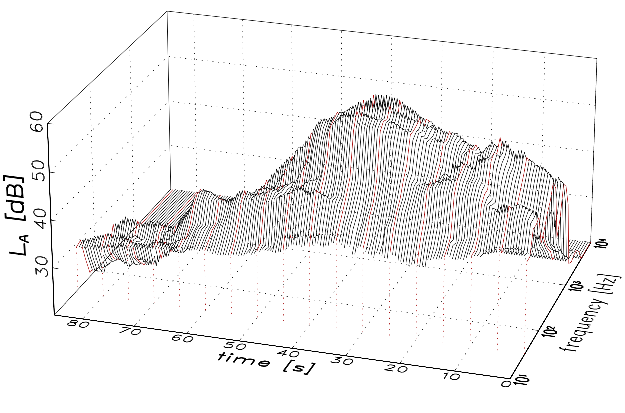

Fig. 5 Waterfall presentation of A-weighted spectra of an aircraft passing by in 1/3 octaves re. 20µP / √Hz.

Clearly is present the shifting of the aircraft noise from an higher frequency component level to a lower one as times goes by. The sound radiation is angle-dependent, easily described in the aircraft coordinate frame.
By using such spectra of the aircraft event in Fig. 4 the flight path and the frequency dependent attenuation of sound by the atmosphere, the soundscape of Castricum of the aircraft is generated, which is shown by Fig. 6.

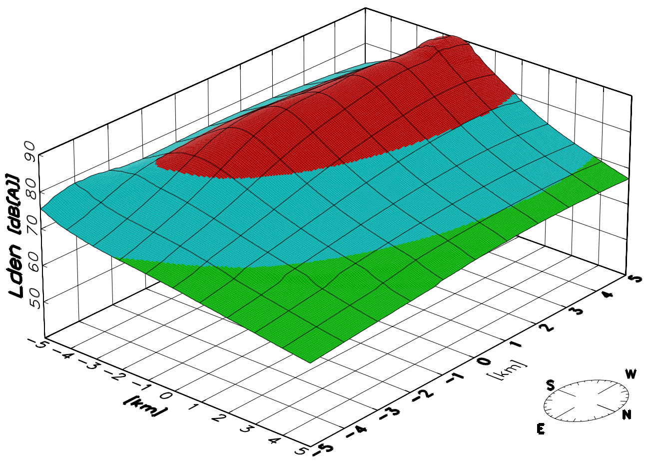

Fig. 6 A soundscape generated from the aircraft noise shown in Fig. 4.

The contributions of all aircraft can be added giving a periodically objective measure for the aircraft annoyance experienced by neighbors of airfields. This objective annoyance figure can be related to personal annoyance or population intolerance for aircraft sound. The Wyle report is an example of such investigation, to objectify complains about annoyance, concentration loss and even health issues like heart disease.

Conclusion

An effective system has been developed to relate complains in an objective manner to aircraft noise. The system is based on new signal processing techniques combined with optimal estimation. A new phenomenon, the Doppler angular has been used in the calculation of the flight path besides the classical method with two or more distant monitoring systems. The monitoring system has been evaluated by Botteldooren in order of the Ministry of Traffic and Waterways of the Dutch government [2].
The hardware costs are low due to the advanced signal processing costs and the off-the-shelf components.

Acknowledgments

I highly appreciated the initiative of Bram Koppert of the Ministry of the Traffic and Waterways to have the system evaluated. His initiative was not appreciated by the Ministry and resulted in his early retirement of Bram [4].
This was contrary tot the Dutch government policy about innovations.

References

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[3] B. Albee and X. Jessurun, Wyle Report, 'Nighttime noise criteria and land-use guidelines for the city of High Point', Feb. 2003

[4] Private communication with the author.