Proceedings of 20th International Congress on Acoustics, ICA 2010

23–27 August 2010, Sydney, Australia

A measurement method to discriminate aircraft fly-over noise

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PACS: T43.20.Ye 43.50.Lj 43.50.Rq 43.50.Yw

ABSTRACT

Currently aircraft noise monitoring systems use a mesh of single microphones distributed around an airport to continuously sample the noise level. This fact requires a manual process of aircraft noise event detection and classification in order to distinguish aircraft events from the rest of noise events in the recording. In the present paper a 3-meter-long 12-microphone linear array is used to automatically obtain a background noise free aircraft noise recording. The beamforming process separates the noise impinging in the array from above (potential aircraft noise) and the noise impinging from below (urban noise and reflections), the results are enhanced by the use of a trigger condition on the difference between both. The theoretical results reveals that the background noise in the aircraft noise recording can be attenuated by about 8 dB if the microphone array is optimally placed. The experimental tests shows that even in non optimal placements the array still provides better results than a single microphone if the threshold value in the trigger condition is properly set.

INTRODUCTION

When measuring aircraft noise, background noise becomes a problem. Currently, aircraft noise monitoring systems are integrated by a net of components including noise monitoring terminals (NMT) that measure the environmental noise, the traffic control radar that collects aircraft flight tracks, devices collecting meteorological data, and even systems that collects citizens complains about aircraft noise [1]. Focussing in the NMTs, they have to provide aircraft-specific noise levels, therefore the background noise of their placement site have to be insignificant or otherwise removed somehow.

Searching for insignificant background noise levels means to restrict the placement of the NMT to quite areas. Unluckily, urban areas are hardly quite, and at the same time they are the areas where aircraft noise data is relevant if the aircraft noise impact on the population wants to be controlled. Therefore, the option of removing background noise has to be studied.

Background noise can affect the measurement in two different ways:

- Noise events other than aircraft fly-over appear in the noise level time history and they have to be differentiated from the aircraft ones. This is generally done in two steps. First of all, the possible aircraft noise events are detected using a sound level threshold on the acoustic signal as a trigger, in that way, noise events too low to be generated by aircraft fly-over are discarded [2]. The second step consists on correlating the noise events with flight tracking data. However, this data is often provided with some delay for security purposes disabling the option of real-time aircraft noise fly-over discrimination, and moreover, in small airports where light aircrafts operate this data is often not available at all.

- Other noise events can happen simultaneously to aircraft fly-over. In that case, as the aircraft fly-over is detected by the threshold method, all the noise is assumed to be generated by the airplane overestimating its noise impact.

In the present paper a microphone linear array is used to discriminate aircraft fly-over noise from background noise [3, 4, 5, 6]. A microphone linear arrays is capable of isolate the sound waves that impinges on the array in a certain angle like a spatial filter. Therefore, if the array is placed in a high position (terrace, roof...) that guarantees that all the traffic and urban noises comes from below, and aircraft noise comes from above, the contribution of aircraft noise can be isolated and so background noise is removed. Moreover, aircraft noise reflections are also erased since they come from below the array, therefore the results can be used to correlate experimental with simulated data because aircraft noise simulation software tends to not include the contribution of sound reflections.

When using a microphone array as an NMT instead of a single microphone, no correlation with aircraft tracking data is needed since noise events other than aircraft fly-over noise have already been removed. Also, in case of simultaneous noise events, just the aircraft contribution is taken into account.

BEAMFORMING

The use of a linear array allows to determine the vertical angle of incidence of the sound waves on the array, a 2D microphone array allows to determine the direction of arrival (vertical and horizontal angles of incidence) of the impinging sound waves, and a 3D microphone array allows to completely locate the sound source (vertical and horizontal angles of incidence, and range).

Aircraft fly-over noise and traffic noise will impinge on the array clearly in different angles if the array is placed vertically in a roof or terrace. Taking the horizontal line that crosses the highest microphone (reference microphone from now on) as 0° reference, aircraft noise impinges on the array in positive angles while urban noise and reflections impinge on it in negative angles as it is shown in Figure 1

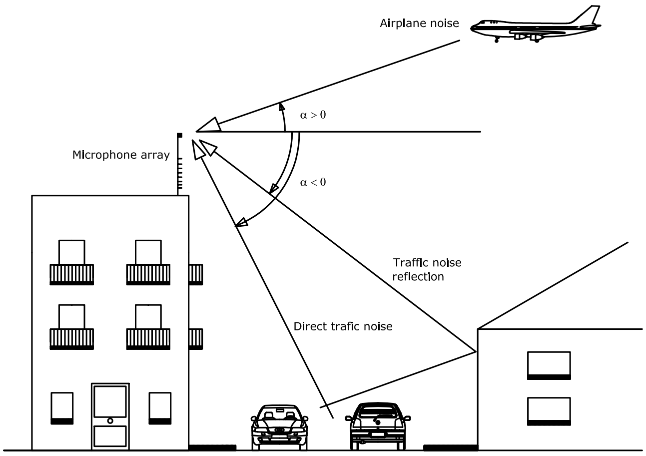

Figure 1: Microphone array placement and incidence angles of the sources

The method used in this paper to isolate the noise contribution of the aircraft assumes that the wave fronts are plane when they reach the microphone array. This assumption holds due to the large distance between the noise sources and the microphone array. Figure 2 shows a plane wave impinging on the array.

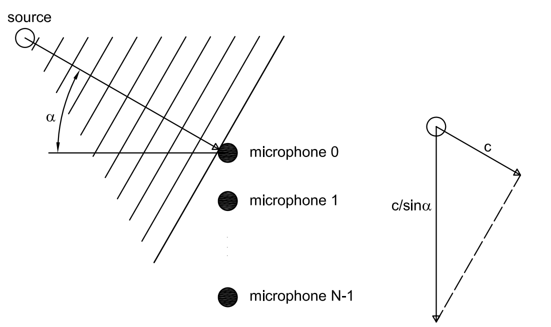

Figure 2: Plane wave impinging on the microphone array

The wave front doesn't reach all microphones at the same time, and the propagating speed of the sound wave along the microphone array depends on the angle of incidence Eq.(1).

$$c' = c/\sin\alpha \qquad (1)$$

Rewritting Eq.(1) in terms of frequency (f) and spatial frequency (v') results in:

$$v' = (f/c)\sin\alpha \qquad (2)$$

This means that for every sound wave, the ratio between temporal frequency and spatial frequency in the microphone array direction depends on the incidence angle. Therefore, the goal here is to decompose the acoustic field as a function of these two magnitudes. A double Fourier Transform is used in order to convert from the time domain to the frequency domain and from spatial domain to spatial frequency domain. If the double Fourier Transform is applied on the microphone signals $p(d_i,t)$ to transform them to the temporal frequency-spatial frequency domain $P(v',f)$ both time and space need to be periodically sampled. This requieres the distance between two adjacent microphones to be constant. However, the double Fourier Transform can also be applied on the Cross Correlation Function of every couple of microphones $R(\Delta d,t)$,in that case what needs to be periodically distributed is the distance between microphone pairs (Δd) and not the absolute position of the microphones. Let d_i be the absolute position of the microphone i measured as the distance from the reference microphone, then the distance between any pair of microphones has to be a multiple of a fundamental distance d, and a pair of microphones have to exist for every multiple up to the highest value K of the series.

$$\Delta d_{ij} = d_i - d_j = k.d \;\; with \;\; k = 0,1,2,3,4...K \qquad (3)$$

In practise, the beamforming is completely done in the temporal frequency domain, thus, the first step involves the calculation of the Digital Fourier Transform of the microphone signal.

$$P(d_i, m\Delta f) = \frac{1}{N}\sum_{n=0}^{N-1} p(d_i, n\Delta t)e^{-j\frac{2\pi nm}{N}} \qquad (4)$$

In the next step the Cross Spectrum between every microphone pair is calculated.

$$G(kd, m\Delta f) = P^*(d_i, m\Delta f)\cdot P(d_j, m\Delta f) \;\; with \;\; k = \frac{d_i - d_j}{d} \qquad (5)$$

The last step is to transform from the spatial domain to spatial frequency domain.

$$A(h\Delta v', m\Delta f) = \frac{1}{2K+1}\sum_{k=-K}^{K} G(kd, m\Delta f)\cdot e^{j2\pi hk/2K-1} \qquad (6)$$

In Eq.(6) the summation is performed over positive and negative values of k because negative values are also available since

$$G(kd, m\Delta f) = G^*(-kd, m\Delta f) \qquad (7)$$

In that way the aperture of the microphone array is synthetically doubled.

The discrete version of Eq.(2) points that for every pair (h,m) there is an associated angle of incidence

$$\sin\alpha = (\frac{h\Delta v' c}{m\Delta f}) \qquad (8)$$

Therefore the power spectrum of the sound waves impinging in a specific angle of incidence is

$$A(\alpha, m\Delta f) = A(h\Delta v', m\Delta f) \;\; where \;\; \alpha = \arcsin(\frac{h\Delta v' c}{m\Delta f}) \qquad (9)$$

Once the Power Spectrum of the sound field is decomposed regarding to the incidence angle of the sound waves, it is integrated over positive angles, and over negative angles. For both range of angles, the power spectra is integrated in octave bands and A–weighted to obtain $LA_{eq_{1s}}^{\alpha<0}$ and $LA_{eq_{1s}}^{\alpha>0}$

MICROPHONE ARRAY GEOMETRY

The length of the microphone array (X) has to be small enought so that the device is easy to mount and doesn't requiere to be supported by an auxiliary structure. Given that, the length of the array has been set to 3 m, therefore X=K.d=3m. The fundamental distance d has to be chosen so that spatial aliasing is avoided, then

$$d \leq \lambda_{min}/2 \tag{10}$$

The main aircraft noise contribution happens within 125 to 2 000 Hz octave bands [3], as a consequence λ_{min} is given by the highest frequency in the 2000 Hz octave band, and d=0.06m, therefore,K=50. The minimum number of microphones requiered to cover a length of 3 m with a fundamental distance of 0.06 m is 12 if they are distributed as follows [7]

$$[\ 0\ 1\ 2\ 3\ 23\ 28\ 32\ 36\ 40\ 44\ 47\ 50\ ].d$$

The integers in the brackets are multiples of the fundamental distance d, in a way that the reference microphone (microphone 1) is placed at position 0 in the linear array (higherst end), microphone 2 is placed 1d under microphone 1, microphone 3 is placed 2d under microphone 1 . . .

Regarding what has been said in eq.7, the synthetic aperture of the microphone array will be $2X = 6m$

RESOLVING POWER

Differentiating Eq.(2) the angular resolution of the microphone array is

$$\Delta\alpha = \frac{\Delta\nu' c}{f \cos\alpha} \quad where \quad \Delta\nu' = \frac{1}{2X} \tag{11}$$

It can be seen that the angular resolution is a function of the sound waves frequency f, and the incidence angle so that best resolution is found for higherst frequencies and incidence angles close to 0°.Table 1 shows the resolution values for f=125Hz

Due to the leakage effect in the spatial Fourier Transform, if $A(\alpha, m\Delta f)$ is plotted for a given frequency as a function of α, the angular spectrum of a sound wave that impinges on the array with a certain angle will not appear as a single spectral line but a main lobe and a set of secondary lobes. The bandwidth of the main lobe 3 dB under the peak is $0.89\Delta\alpha$ for rectangular spatial window, this means that two sound waves of the same amplitude will be resolved if they impinge on the array with a difference of $B_\alpha = 0.89\Delta\alpha$, this would be the resolving power of the microphone array.

Table 1: Angular resolution and resolving power when f=125Hz

$\alpha(°)$	0	±10	±20	±30	±40	±50	±60	±70	±80
$\Delta\alpha(°)$	26	26.4	27.6	30	33.9	40.4	51.9	75.9	149.6
$B_\alpha(°)$	23.1	23.5	24.6	26.7	30.2	36	46.2	67.6	133.1

The traffic noise impinging within 0°and −20° could not be differentiated from the noise impinging within 5°-10° (lowest incidence angle for aircraft noise) regarding the resolving power shown at Table 1.Also urban noise impinging with lower angles than −70° couldn't be distinguished from noise within 5°-10°. This facts restricts the microphone array placement to sites that guarantee that no significant urban noise or its reflections are seen over −20° or under −70°.

Figure 3 shows the results obtained from a computer simulation of the array response when a sound wave impinges on it at an incidence angle of −20° (the maximum allowable angle for traffic noise). The level of the impinging noise is 70 dB at the array, and the results are shown for single frequency waves of different frequencies. It can be seen that just in the case of low frequency, the main lobe extends up to positive angles.

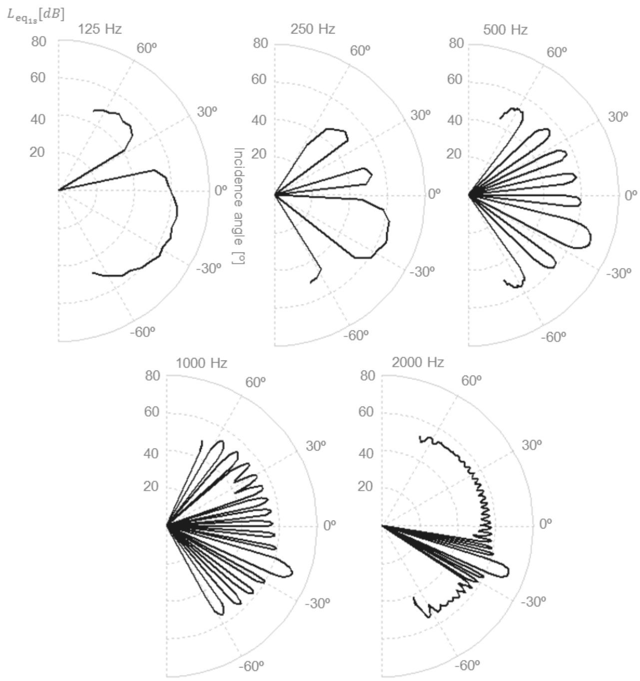

Figure 3: Array output for a single wave impinging with −20°. The wave frequency is 125, 250,500, 1 000 and 2 000 Hz (same scale for all diagrams). The metric used is the Leq1s

TRIGGER

Besides the main lobe, the effect of secondary lobes is also relevant. Table 2 shows the noise level of Figure 3 integrated over aircraft noise angles(10° to 90°) and negative angles (0° to 90°).It can be seen that even when there is no sound waves impinging on the positive angle range, the $LA_{eq_{1s}}^{10°<\alpha<90°}$ is not 0 due to the presence of the secondary lobes of the sources in the negative angles quadrant.

Table 2: $LA_{eq_{1s}}^{\alpha}$ when f=125Hz

f	125	250	500	1000	2000
$LA_{eq_{1s}}^{10°<\alpha<90°}$	56.1	57.1	57.8	59.9	62.3
$LA_{eq_{1s}}^{-90°<\alpha<0°}$	70.1	70.1	69.9	69.9	70.2

The presence in the positive quadrant of side lobes of sources in the negative quadrant, and part of the main lobe in the case of low frequencies, will have two main consequences:

- There will be residual background noise in the positive angles noise level time history caused by urban noise. This effect is not significant since the remaining background noise is in the worst case 8dB lower than the urban noise ($LA_{eq_{1s}}^{-90°<\alpha<0°}$) (see Table 2). This means that when an aircraft is flying over the remaining background noise would be negligible compared to the aircraft noise, or at least much lower than the background noise that would be measured by a single microphone.

- The positive angles noise level time history will not be 0 dB when no aircraft is flying over. To overcome this situation a trigger is used to detect aircraft fly-over.

When no aircraft noise is present the difference between $LA_{eq_{1s}}^{\alpha>0^\circ}$ and $LA_{eq_{1s}}^{\alpha<0^\circ}$ will remain approximately constant due to the fact that $LA_{eq_{1s}}^{\alpha>0^\circ}$ is strictly caused by the secondary lobes of the sources $\alpha < 0$, so if $LA_{eq_{1s}}^{\alpha<0^\circ}$ increases $LA_{eq_{1s}}^{\alpha>0^\circ}$ increases in proportion. However, when aircraft noise is present in $\alpha > 0$ the proportionality is broken. This fact is used to detect when aircraft noise is impinging on the array and used as trigger, so just when the proportionality is broken $LA_{eq_{1s}}^{airplane} = LA_{eq_{1s}}^{\alpha>0^\circ}$, otherwise $LA_{eq_{1s}}^{airplane} = 0dB$

OUTDOOR EXPERIMENTAL RESULTS

Low cost microphones Behringer ECM 8000 are used in the array, they are corrected in amplitude and phase in order to ensure that all of them have the same frequency response. An anti aliasing filter with a cut off frequency slightly higher than the highest frequency of the range of interest is used before the signals are acquired at a sampling frequency of 8.192 Hz, the data is truncated in blocks of 8192 samples to be processed, in that way the averaging time is 1 second. The data is acquired with three ADLINK PXI-2006 acquisition cards synchronized with an external timer ADLINK cPCI-8554/R, and it is processed using the software MATLAB. In Figure 4 the different steps involved in the $x_i(t)$ refers to the signal of the ith microphone and $x_i(n\Delta t) = p(d_i, n\Delta t)$ signal conditioning, acquisition and processing are shown.

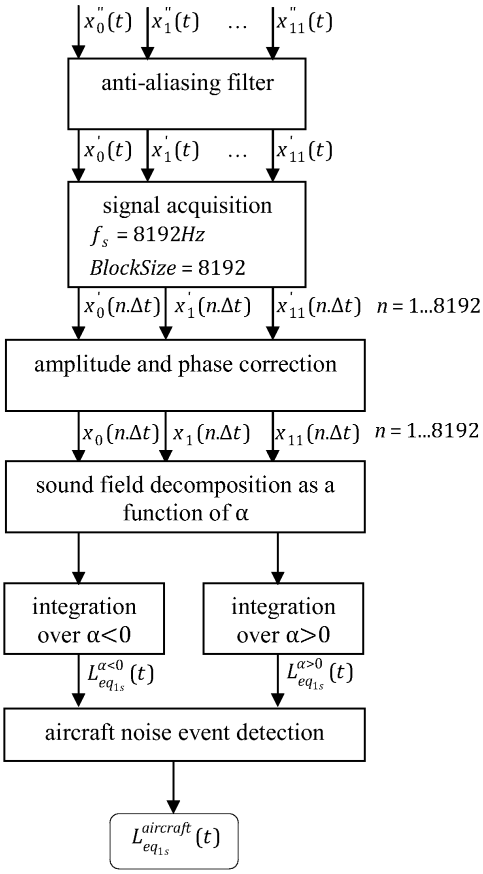

Figure 4: Signal conditoning, acquisition and processing block diagram

The microphone array was tested in the surroundings of the Mallorca Airport. As can be seen in Figure 5 noise from airplanes but also traffic noise impinged on the microphone array. The microphone array was placed at the top of a 3 m height old mill, due to the low height of the building traffic noise from distant roads was seen at negative angles close to 0° as well as the taxiing noise from the airport. This is an unfavourable circumstance for the performance of the microphone array because it increases the residual background noise in the positive quadrant.

Figure 5: Microphone array location in the outdoor experimental test

Figure 6 shows the noise level time history recordings obtained after the beamforming in the positive and negative quadrant for different frequencies. The two higherst peaks are caused by aircraft fly-over. It can be seen how the $LA_{eq_{1s}}^{\alpha>0^\circ}$ time history is lower than $LA_{eq_{1s}}^{\alpha<0^\circ}$ time history, and that the difference between both keeps approximately constant unless an airplane is over flying the microphone array. It can also be seen that the placement of the array affects specially at low frequencies, at which the difference between $LA_{eq_{1s}}^{\alpha>0^\circ}$ and $LA_{eq_{1s}}^{\alpha<0^\circ}$ gets smaller which means that the residual background noise in the positive quadrant won't be largely reduced.

Figure 7zooms in the area around an aircraft noise event in the total noise level time history to show how the difference between $LA_{eq_{1s}}^{\alpha>0^\circ}$ and $LA_{eq_{1s}}^{\alpha<0^\circ}$ reduces up to the point where $LA_{eq_{1s}}^{\alpha>0^\circ}$ is higher than $LA_{eq_{1s}}^{\alpha<0^\circ}$. The urban noise register increases when an aircraft is flying over due to the secondary lobes that appears in the negative quadrant but also due to the aircraft noise reflections that impinges on the array at negative angles. In that case, due to the microphone array placement, the difference between $LA_{eq_{1s}}^{\alpha<0^\circ}$ and $LA_{eq_{1s}}^{\alpha>0^\circ}$ is always higher than 4 dB when there is no aircraft fly-over, therefore the trigger condition is set to be: $LA_{eq_{1s}}^{\alpha<0^\circ} - LA_{eq_{1s}}^{\alpha>0^\circ} < 4dB$. for every different placement of the array previous measurements have to be done in order to establish the threshold level of the trigger condition. As said before it mostly depends on the angle of incidence of the urban noise sources in that specific placement.

Figure 8 shows a comparison between the result obtained by the microphone array after the triggering is done, and the result obtained from a sound meter level. It can be seen how when there is an aircraft over-fly, the microphone array time history is lower than the sound meter level time history because in the former no aircraft noise reflections are acounted and also the background noise is widely reduced.

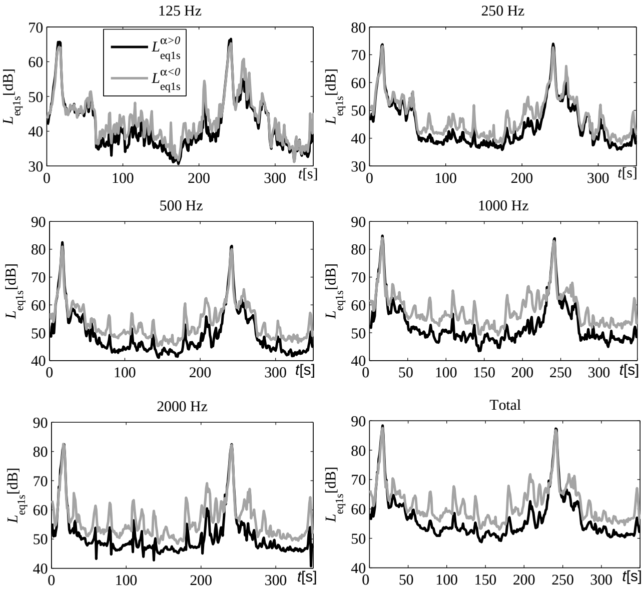

Figure 6: $LA_{eq_{1s}}^{\alpha>0^\circ}$ and $LA_{eq_{1s}}^{\alpha<0^\circ}$ sound level time histories obtained after beamforming for each octave band

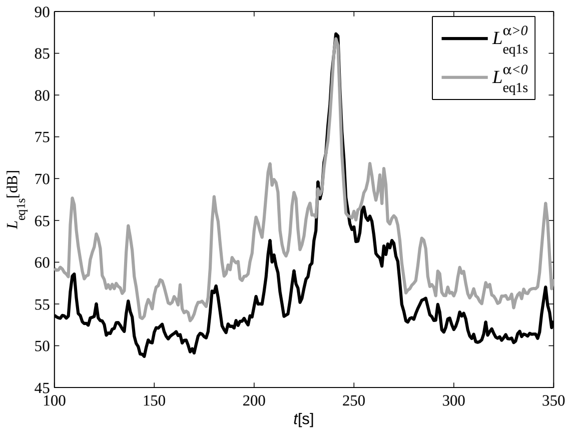

Figure 7: $LA_{eq_{1s}}^{\alpha>0^\circ}$ and $LA_{eq_{1s}}^{\alpha<0^\circ}$ total sound level time histories obtained after beamforming. Zoom in around an aircraft noise event

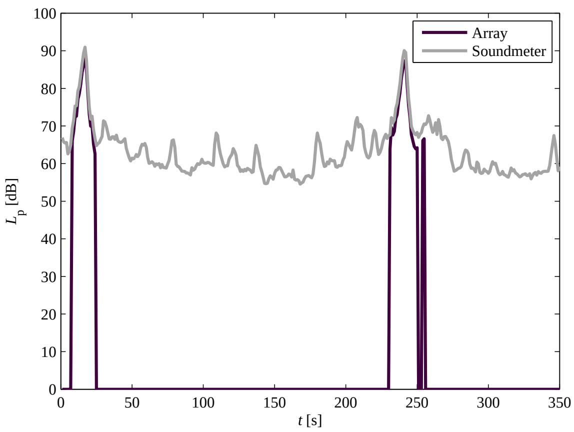

Figure 8: Microphone array final ouptut compared to sound meter level output

CONCLUSIONS

This paper proves that a linear sparse microphone array of 12 elements and 3 meters long can be used to obtain an aircraft noise time history not influenced by extraneous noise such as traffic noise or other sorts of urban noises. This device can be used in a wide range of urban placements where no urban noise impinges over $-20°$, or under $-70°$. The frequency range of use goes from 125Hz to 2 kHz octave bands.

Beamforming is not enough to provide an aircraft noise time history free of background noise. Spatial leakeage effect causes sides lobes to appear in the positve quadrant when urban sources are present, and as a consequence the output of the antena is different from 0 dB when no aircraft is flying over.Therefore, an extra step to the processing algorithm is added to identify aircraft noise events.This step consists of a triggering condition on the difference between $LA_{eq_{1s}}^{\alpha>0^\circ}$ and $LA_{eq_{1s}}^{\alpha<0^\circ}$. The threshold value of the trigger depends on the array placement, thus, it is suggested to make a previous study of the source's angle of incidence on the array, and then adjust the trigger value.

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