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Assessing environmental noise impact of PA systems with the swept-sine method. A case study in the heritage site of the Alhambra

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Declaration of interests:

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J.A. and J.R. conceived of the presented idea. J.A., R.G, J.R. and F.J.M. took part in the field measurements. J.A. developed the theory and performed the computations. R.G. and A.R. verified the analytical methods. J.A. wrote the manuscript with support from R.G., F. J.M. and A.R.. A.R. supervised the findings of this work. All authors discussed the results and contributed to the final manuscript.

ABSTRACT

Open-air spectacles near populated areas can cause noise issues. Sound engineers need an estimation of the limits at their mixing desk to avoid noise regulation infringements in places that can be far away. The Swept Sine Method is well known to set up sound systems among other uses but has never been used to assess long distance noise levels. This technique allowed a quick estimation in a neighbourhood with noise complaints caused by a theatre located on the other side of a valley. Traditional methods like sound level meter measurements failed as background noise was higher than the levels to be measured. This method can be applied to any situation where the noise source is electroacoustic.

1. INTRODUCTION

Noise is an undeniable widespread health problem [1] and it is predicted to keep growing in Europe [2]. Its health effects are becoming increasingly well-known including auditory problems, sleep disturbance or cardiovascular diseases [3],[4],[5],[6]. Twenty-two million people suffer chronic high annoyance and 6.5 million suffer from chronic high sleep disturbance due to noise exposure [7]. Road traffic is the most important source of noise exposure in Europe by far. It is even higher in urban areas according to the last reference. Only a few annoyance studies compare sources not modelled in noise maps (traffic, railways, planes and industry) [8], [9].

Noise-induced annoyance is one person's individual adverse reaction to noise according to [10] so the same sound can have a different effect on different individuals. Hence, the relationship between noise and perceived annoyance is complex [11],[12],[13]. Personal interpretation of noise depends of course on its acoustic properties, such as intensity, duration and frequency, but also on other factors, such as location, time, and personal factors such as sensitivity to noise [14], [15] but also from a semiotic point of view [16], each perceived sound is a carrier of information and can hence be analysed as a sign carrier [17], [18]. I.e., cultural differences can influence the unpleasantness sensation of a sound [19]. Annoyance is assessed as the percentage of highly annoyed people (%HA) [11] made during a standardized survey. The perception of people may not match with measured noise levels [8].

Outdoors concerts and festivals have become frequent near every city and with them a lot of noise problems for the population of the surroundings. Public address (PA) systems used in these venues have commonly a high and complex directivity as line arrays [20]. Recommended noise mapping methods like [21] cannot deal with such complex directivities as only a simple directivity correction is allowed. This kind of systems can be steered by physical or electronic ways. This is usually simulated with software developed by their brand but of course, it is intended for coverage estimation of the audience and not to predict noise levels far away.

Environmental noise assessment and management in Europe is regulated by the directive [22] and local regulations derive from it. Also, noise determination procedures are standardised by [23] so measuring with sound level meters is the mandatory way to assess noise compliance. However, it is a must to have enough signal-to-noise ratio (SNR). Level corrections for background noise are available but if the residual sound pressure level is 3 dB or less below the measured sound pressure level, no corrections are allowed [23].

Impulse response extraction by deconvolution of exponential swept-sines (ESS method) improves SNR [24]. This technique is a standard method for audio engineers [25][26][27], acousticians for room parameters estimation such as reverberation time [28], sound insulation[29], sound barriers [30], dynamic stiffness [31], or even indirect measurement of temperature [32]. The noise level coming from a far source can be assessed if the level and attenuation from a point closer to the source are known. This enables the assessment when residual noise corrections are not allowed and allows assessing the levels in different points by monitoring only a reference point near the source. ESS method has demonstrated to be reliable for insulation measurements [29] which is a kind of attenuation and measuring below background noise [32] due to its great noise and distortion rejection [24][26]. ESS method can, therefore, aid sound engineers and acoustic consultants in assessing the impact of any electroacoustic source and to make decisions based upon these assessments.

This article proposes the use of the ESS method to estimate the noise produced by loudspeakers at great distances, adapting the usual procedures to overcome the issues related to the particular problem. It presents a case study on the effects of the spectacles at the open-air theatre of Generalife on the Albaicín neighbourhood, both places in the surroundings of the Alhambra complex as example and validation. The next sections will follow the next structure: Material and methods introduce the measurement scenario and campaign; Theory and calculation explain the state of the art on ESS method and the calculations to assess the noise levels; Results and discussion show the assessed noise levels and explains the improvements and weaknesses of the technique extracting more information of results and Conclusion reviews the validity of the method and interprets the meaning of the results.

2. MATERIAL AND METHODS

2.1. The Generalife and the Albaicín neighbourhood

The Generalife is an architectural complex conceived as an annexed villa to the Alhambra for the Muslim kings and composed of gardens, orchards, and architecture. It has been declared a World Heritage Site by UNESCO together with the Alhambra. The Albaicín is a traditional neighbourhood of Granada, made up of an intricate network of narrow streets between carmens (a type of house built on a hill with a garden and a wall that separates it from the street on the façade facing the valley). The neighbourhood has also been declared a World Heritage Site by UNESCO, as an extension of the Alhambra and Generalife complex. River Darro is located between the Alhambra fortress, its residences, and gardens like Generalife from one side, and the residential district of the old city, Albaicín, from the other.

2.2. The Generalife Theatre

The Generalife has an open-air theatre since 1954, used during the months when the weather permits. It has undergone several adaptations since then, the last one being the restoration in 2005. The theatre takes advantage of the slope of the land to orient the stage towards the neighbourhoods of Albaicín and Sacromonte.

Figure 1. Location of the Theatre

2.3. Electroacoustic reinforcement in the Theatre

The spectacle of which its sound affection is studied is within the program Lorca and Granada in the Gardens of the Generalife. It is titled TIERRA - LORCA Cancionero popular, represented by the Flamenco Ballet of Andalusia and with the special collaboration of Mayte Martín. It needs a sound system to cover the full audience, being the cause of the noise complaints.

Figure 2. PA system of the Theatre

The Public Address (PA from now on) consisted of a line array system from Meyer Sound. Line array systems are groups of loudspeakers that achieve high directivity through the coherent interference of the sources that make up the grouping. In analogy to light, it would be like a spotlight that can be directed on-demand to illuminate areas of interest. Figure 3 shows the 2 kHz octave simulation of the PA system, the aim is to illustrate the directivity of this kind of systems.

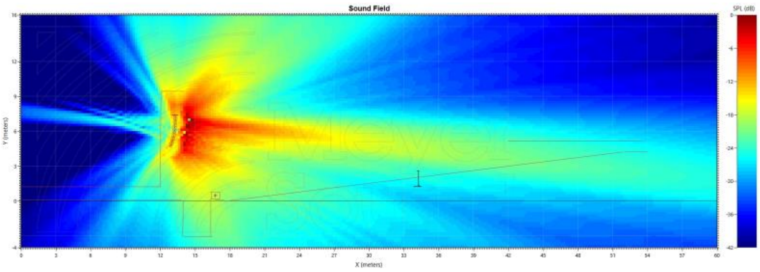

Figure 3. Coverage simulation of the PA system (calculated with Mapp XT)

2.4. Measurement point selection

The points where noise levels could be higher in the Albaicín were selected. The same spectacle was repeated daily. So the points of interest were decided by strolling the Albaicín during the show, looking for places where music could be heard. That decision avoided a lot of possible measurement points which were considered interesting at first instance. Selected points included streets, squares, a restaurant and even a building property of the University of Granada. Samples were recorded in every point of interest. As the recorded signals had a calibration reference, all the parameters a sound level meter can calculate could be assessed by post-processing. That enabled SPL estimation but, as explained in Section 1, it is not possible to: segregate background noise, record the crowning moments in every place, or establish relationships among the points.

Nine points throughout the Albaicín neighbourhood were selected and the mixing desk position in the theatre as the reference point. The measurements consist in reproducing 10 second ESS signals through the PA system previously described at the same level every time. Those signals were recorded with a calibrated portable recorder

(HEAD Acoustics SQuadriga II) and external microphones using 24 bit 48 kHz sampling rate in different places of interest. The records will be used to extract impulse responses (IR) by post-processing to be analysed and compared with the ones obtained in different points of interest.

2.5. ESS recording at the points of interest

The next afternoon, several ESS were played through the PA and recorded at each point of interest.
shows the selected points of interest. GPS was used to locate the points.

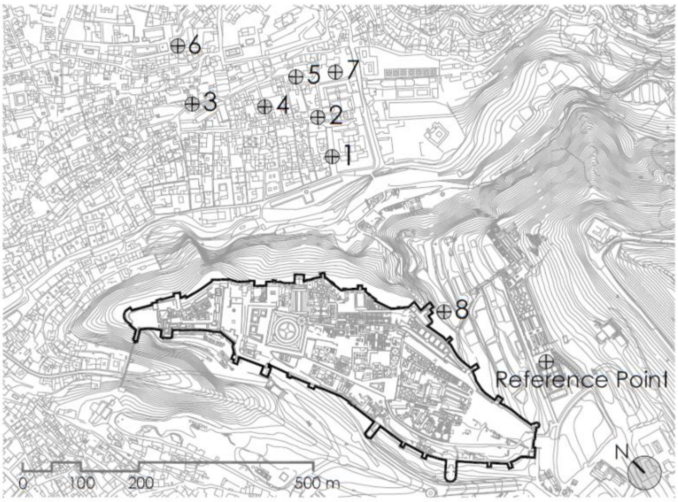

Figure 4. Points of interest

The ESS signals were recorded in the nine points in the following days. Deconvolution by post-processing to obtain the IR and the attenuations (1/3 octave band Level Differences, D) from reference point were calculated. Direction, distance, and elevation were derived from the GPS coordinates.

2.6. Monitoring the mixing desk

Noise spectra can be assessed by convolution in case of previously recorded signals, like recurring announcements. For live applications it is easier to monitor a reference point and calculate the attenuation in frequency bands. The assessed receiving levels are the subtraction of the level at the reference point and the attenuation. Therefore, the levels at the mixing desk shall be monitored. A calibrated microphone placed in the reference point recorded the full spectacle, enabling the calculation of all the acoustic descriptors of interest using ArtemiS software by HEAD acoustics or BK Connect by Brüel & Kjaer. The method allows not only estimating the SPL but also all the other descriptors relevant to make corrections or for further research as C-weighted levels, 1/3-octave levels, or percentiles.

3. THEORY AND CALCULATION

This section explains the assessment procedure. A flowchart is supplied to facilitate the replication of the method in different scenarios. An overview shows the steps to follow and the subsections explain the different tasks in more detail.

- Reference point selection: A reference point must be selected where the electroacoustic devices sound loud and the SPL can be monitored.
- Points of interest selection: At least one point must be selected where the noise from the source should be assessed.
- ESS must be recorded at the same level in reference point and every point of interest. Some repetitions are recommended.
- Deconvolution of ESS preserving the inter-channel gain differences, the authors recommend the use of Aurora plugins in their versions for Audacity [33]
- Analysis of the IR: The authors have used ArtemiS by HEAD acoustics and BK Connect by Brüel and Kjaer, both software solutions are reliable, easy to use, and powerful but expensive. Users experienced in signal

analysis can use a wide range of solutions. The analysis consists in selecting the adequate time-limits of the IR, A-weighting, and 1/n-octave filtering

- IR level subtraction: The attenuation is calculated in every band as the level calculated for the reference point minus the level at the point of interest
- Reference point Monitoring: Can be done with calibrated recordings or SPL-meter in 1/n-octave bands
- SPL estimation at the points of interest: The assessed SPL is the SPL measured at the reference point minus the attenuation.
- Global results, like global A-weighted SPL (L_{Aeq}), will be calculated as the energetic addition of the individually A-weighted 1/n-octave frequency bands.

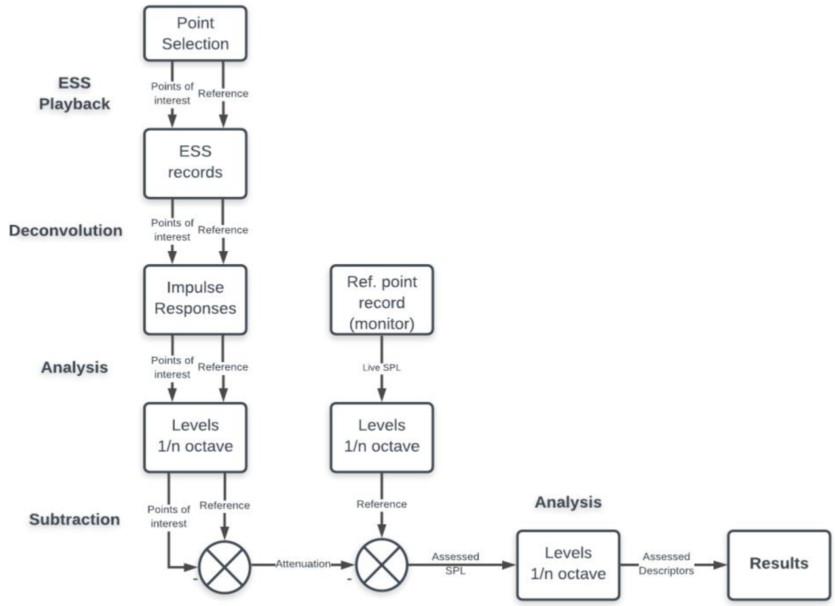

Figure 5. Calculation flowchart

3.1. Calculation of impulse responses

The IR of a linear time-invariant system can be retrieved in the time domain by convolving the device under test's (DUT) response with the inverse filter [26] of the excitation signal. The only must for the signal is to be deterministic but is also desired to provide enough energy to excite adequately the band of interest.

The most used signals are sweeps and MLS [34]. A good comparison of the use of both signals can be found in [24]. On one hand, the use of MLS improves the behaviour when pulsive noises are present, show no pre-ringing effects and require less computational power. Pre-ringing can be avoided and computational power is not an issue when IR extraction is made by post-processing with usual computers. On the other hand, the advantages of using sweeps include the segregation of harmonic distortion [27] leading to a better effective signal-to-noise ratio (ESNR) as defined in [29]. Sweeps also exhibit better behaviour with non-stationary conditions such as atmospheric inhomogeneities like wind or humidity or temperature. This is especially true when single long sweeps are used instead of synchronous averaged ones.

In this case, we have all the kinds of possible problems: High distortion due to high SPL in the theatre, low SNR due to attenuation and high background noise (random, tonal and pulsive) and large effects of atmospheric inhomogeneities due to long distances. Swept-sines are the best choice and problems related to pulsive noises are a lesser evil. Working in environmental acoustics it is useful to use pink spectrum excitation signals so in case of the constant amplitude swept-sine it should change its frequency exponentially (ESS). Non-white signals' inverse filters must be constructed in the frequency domain by FFT, inversion and then IFFT. Longer sweeps provide better ESNR but they are unpleasant. A 10-second length was used but further research to find an optimum would be desirable.

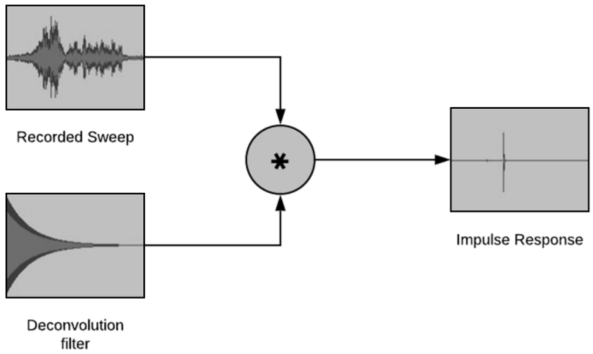

Figure 6. Impulse response extraction

The usual way to obtain the IR is using a full-duplex sound card with appropriate software but that was not possible as would have required hundreds of meters of wire crossing a valley with a river and buildings. Neither wireless microphones would have solved the problem as buildings avoided the direct vision of the theatre. Clock-drifting can be a source of distortion (skewing) of the obtained IR [35], [24] but no signs of it were observed and we were unable to test the playback device. Compensation by resampling or filtering is desirable but one of the great advantages of the ESS method over other methods for measuring the impulse response is that a tight synchronization between the playback clock and the recording clock is not required [36]. Aurora for Audacity [33] is a free and powerful tool to obtain the IR. There are many software solutions to obtain IR but most of them are intended for room acoustics and maximize the resulting audio file losing the inter-channel gain differences.

3.2. Assessment of the quality of the computed impulse responses (ESNR)

ISO-18233 [29] defines the “effective signal-to-noise ratio” (ESNR from now on) as ten times the logarithm to the base 10 of the ratio of the mean-square value of the signal part caused by the excitation and obtained by the new method, to the mean-square value of the unwanted part of the signal obtained by the same method and caused by sources other than the excitation. The aim is to obtain an effective signal-to-noise ratio exceeding or equal to the required signal-to-noise ratio in the classical method. This SNR required in the classical method is >10 dB (or 6 dB if corrected with background noise). The equation looks simpler in terms of L_{eq} (time-averaged RMS SPL).

$$ESNR = 10\log\left[\frac{\frac{\int_{T_1}^{T_2} h_n^2\,dt}{T_2 - T_1}}{\frac{\int_{T_3}^{T_4} h_n^2\,dt}{T_4 - T_3}}\right] = Leq, t_{(1-2)} - Leq, t_{(3-4)} \tag{1}$$

While this definition looks quite straightforward, the chosen time limits for the RMS of the signal part caused by the excitation can affect dramatically the results of the ESNR. Norsonic is one (if not the only one) company that implemented the ISO 18233 method [29], [37] in their sound level meters. Their literature describes the method [38]. According to Ole-Herman Bjor (Norsonic senior scientist), in their realization for ISO 18233 measurements, the broad-band impulse-response obtained from the sweep is filtered in 1/3-octave bands. The initial part, normally with a reverberation, can in most cases be identified and the SNR ratio can be calculated. Time limits are chosen from just before the beginning of the impulse to a time where the impulse again is below the background noise. For measurements in a room, the length of integration is typically half of the estimated reverberation time. The noise signal is obtained by integrating the decay for a time similar to the duration. The noise is obtained by integration over a time interval of similar length as in the impulse part, but at a later time where the impulse has decayed below the noise-floor and the impulse has to be squared before integration. Care must be taken in the selection of time interval T_1-T_2 as T_1 must be a value slightly before the beginning of the IR and T_2 before the noise of the decay curve becomes dominant.

Open-air impulse responses have no reverberation by definition but the observed energetic decay is quite similar. Figure 8 shows the Energy-Time curve of two measurements including their Schröder integral. We decided the final time of integration (T_2) following this criterion using the worst impulse response of the measured in terms of ESNR, which was one of the receiver points and the same time-lapse (T_2-T_1) was used for every measurement. Those time-lapses were analysed to calculate 1/3 octave band L_{eq} of every IR, according to IEC [39]. All the post-processing was made using ArtemiS SUITE by HEAD Acoustics and BK Connect by Brüel & Kjaer.

3.3. Estimating the attenuation between two points

The attenuation between a reference point "r" and a point "n" where noise levels will be assessed can be calculated by pressure integration over the obtained IR. This is done avoiding the Fourier Transform of the IR to obtain the Complex Transfer Function. In our case "r" is the mixing console.

$$D_{\mathrm{r-n}} = 10 \log \left[\frac{\int_{T_1}^{T_2} h_{\mathrm{r}}^2 \, dt}{\int_{T_1}^{T_2} h_{\mathrm{n}}^2 \, dt} \right] = L_{eq,r,t_{(1-2)}} - L_{eq,n,t_{(1-2)}} \tag{2}$$

Attenuation has been called D in analogy to Level Difference as defined in [29] and it is calculated according to the standard. The approach used in the paper is to obtain 1/3 octave values of attenuation according to [39].

3.4. Estimating the Noise levels in the points of interest

The received A-weighted noise level (L_{Aeq} caused by the concert) in point "n" is assessed as the sum of the individual 1/3 octave band A-weighted levels in the reference point "r" measured during the concert $L_{Aeq,r,f}$ minus the attenuation ($D_{r-n,f}$).

$$L_{Aeq,n} = 10 \cdot log \left(\sum_{f=1}^{31} 10^{\frac{L_{Aeq,r,f} - D_{r-n,f}}{10}} \right) \tag{3}$$

Being f the 1/3 octave filter number: (1 is 20 Hz and 31 is 20 kHz).

A full spectacle was recorded at the reference point. A calibrator was used at the beginning of the recording as a reference. All the interesting parameters are calculated, like L_{Aeq}, L_{Ceq}, 1/3 octave analysis or Maximum levels enabling a complete assessment of the noise descriptors.

4. RESULTS AND DISCUSSION

This section shows the steps to calculate the received A-weighted noise level in every point of interest in Albaicín. For this purpose, the ESNR of every IR and the attenuation (D) in every point are calculated. The analysis of the recording of the show, made at the reference point of the theatre was used to estimate the expected noise levels with a particular focus on the point of higher exposure.

Measurement	P1	P2	P3	P4	P5	P6	P7	P8
Direction (º)	316	319	308	314	319	313	325	303
hor. angle (º)	24	21	32	26	21	28	16	37
distance (m)	539	606	779	682	683	847	649	218
elevation (m)	-84.1	-69.5	-61.6	-66.0	-55.5	-29,0	-56.5	-56.9
ver. angle (º)	-8.87	-6.54	-4.52	-5.53	-4.65	-1,96	-4.98	-14.63

Table 1 shows some information about the place and distance every point was from the reference point.

Measurement	P1	P2	P3	P4	P5	P6	P7	P8
Direction (º)	316	319	308	314	319	313	325	303
hor. angle (º)	24	21	32	26	21	28	16	37
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ver. angle (º)	-8.87	-6.54	-4.52	-5.53	-4.65	-1,96	-4.98	-14.63

Table 1. Location of points of interest, from GPS coordinates

The Measured background levels in the Albaicín were extracted from the recordings in the assessment points just before or after the ESS was recorded to assess the background noise from both microphones.

Measurement	P1	P2	P3	P4	P5	P6	P7	P8
LpL (dBA)	59.9	61.5	49.7	49.4	54.1	60.6	60.4	58.9
LpR (dBA)	60.0	62.9	51.0	49.9	55.3	61.7	59.4	55.6

Table 2. Background noise levels

Then, deconvolution of the ESS recordings (raw sweeps) was made. The use of ESS method enabled the measurement of the PA system even below the background noise as previous work noted [24], [26], [27] that traditional SLM measurements could not reach. The spectrograms of raw ESS recording of Figure 7 shows how the sweep is difficult to distinguish from background noise except in the reference point. Low-frequency levels were high and different kinds of noise were found like traffic, voices, or impulsive events.

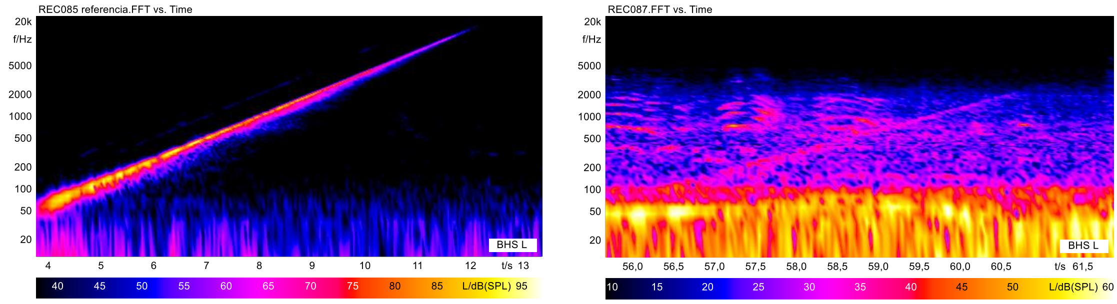


Figure 7. Spectrograms of raw ESS recording of the mixing desk (Reference) and Cuesta de la Victoria (P1)

Figure 8 shows the energy decay of the IR calculated after deconvolution of the same two measurements and also their Schröder integral [40] truncated using ARTA software [41]. Those points were selected because the reference point had the highest ESNR and Point 1 the lowest of all measurements. ARTA was only used to analyse the IR and to help decide the integration limits of equation (1). Truncation is a noise removal method recommended by [28], deeper research can be found on [42].

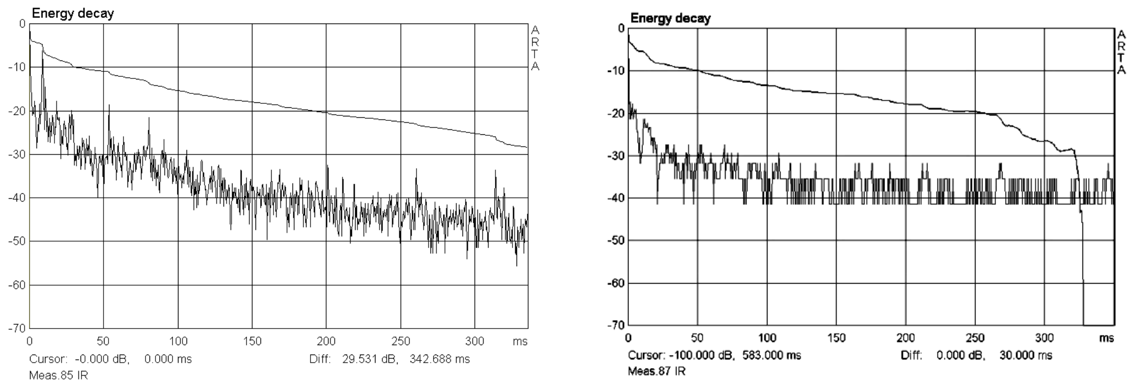


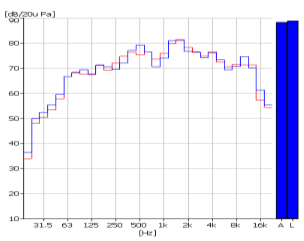
Figure 8. Resulting Impulse Responses of the mixing desk (Reference) and Cuesta de la Victoria (Point 1)

Although the sweep is difficult to distinguish from noise, computed IR is clear and several dB over the background noise. That is the main improvement of the method. Table 3 shows the results of the the effective signal-to-noise ratio (ESNR). The calculations are explained in section 3.2. It must be highlighted that ESNR is strongly dependent on frequency. ESNR values lower than 6 dB mean the attenuation cannot be calculated due to the high background noise while values between 6 and 10 dB should be corrected by energetic subtraction. A 50 ms period after the start of the IR is used to calculate the $L_{eq,n,t(1-2)}$ while the latter part is calculated from 300 ms after the beginning of the IR onwards.

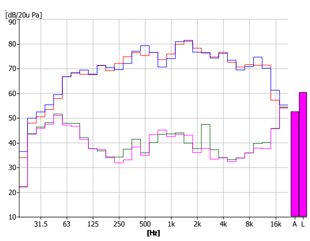
	Ref.	P1	P2	P3	P4	P5	P6	P7	P8
20	29.3	3.3	5.9	14.2	4.5	3.8	0.1	13.4	6.7
25	38.1	15.8	18.3	27.8	18.8	18.4	14.2	29.8	16.8
31,5	41.9	20.7	23.6	28.8	20.3	21.3	18.5	32.5	16.7
40	46.8	19.2	24.9	35.2	23.3	25.2	19.9	33.1	20.3
50	51.4	20.8	24.9	32.5	22.6	21.4	11.7	32.3	21.4
63	47.2	20.2	23.6	34.4	23.5	17.7	16.1	30.4	21.4
80	42.6	20.8	23.6	34.2	21.2	23.8	10.9	28.6	17.2
100	39.9	13.4	19.0	29.6	19.7	19.5	21.8	30.6	13.7
125	30.9	17.5	19.5	28.1	21.1	22.8	20.4	33.9	15.1
160	36.9	16.2	19.1	26.8	17.1	24.5	20.6	31.1	14.3
200	34.7	12.1	18.8	23.8	13.2	19.5	18.3	26.5	16.6
250	36.6	9.5	19.4	23.2	14.8	18.7	18.4	26.0	18.8
315	42.0	12.0	17.1	21.7	14.8	16.5	19.5	25.0	13.8
400	45.3	13.5	18.0	17.8	16.8	18.6	20.1	26.1	12.3
500	43.6	8.0	16.9	20.3	20.2	19.0	19.9	25.9	16.4
630	39.0	11.5	17.8	15.0	15.2	17.0	16.9	26.4	15.6
800	33.3	12.2	16.1	16.5	14.8	15.0	16.1	25.2	18.3
1000	34.8	12.0	15.8	16.0	14.0	16.5	16.4	23.4	16.9
1250	35.7	12.6	14.3	13.8	17.1	14.7	11.6	21.9	18.1
1600	36.2	10.1	14.6	12.8	16.0	12.7	11.8	21.1	16.0
2000	35.1	5.9	12.8	15.1	12.2	10.9	12.4	22.1	15.6
2500	37.1	14.2	12.4	12.5	11.0	11.0	12.2	18.9	9.8
3150	38.3	5.0	11.8	12.7	10.2	13.2	14.1	18.0	10.0
4000	39.0	2.6	12.4	14.8	10.1	12.5	25.3	21.0	8.8
5000	39.1	0.8	10.6	10.0	9.5	10.5	12.2	18.6	8.6
6300	39.7	0.4	7.2	6.8	7.0	6.6	8.1	9.5	7.5
8000	38.8	0.2	4.1	4.8	4.3	3.8	5.1	4.7	5.1
10000	38.4	1.2	2.8	2.3	3.2	3.0	4.3	3.1	4.2
12500	37.8	1.6	4.1	3.6	4.5	4.3	5.5	5.4	6.2
16000	14.6	0.1	0.7	0.6	0.5	0.4	0.6	0.5	0.8
20000	0.8	0.0	0.0	0.2	0.0	0.1	0.2	0.0	-0.2

Table 3. Effective signal-to-noise ratio results (1/3 octave)

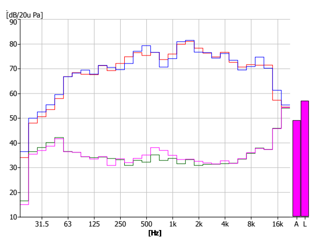
Then, the attenuation is assessed as explained in section 3.3. Figure 9 shows the 1/3 octave band filtered impulse responses of every point. The reference point is included in every graph for ease of comparison. Reference (blue and red) and measured point (pink and green).



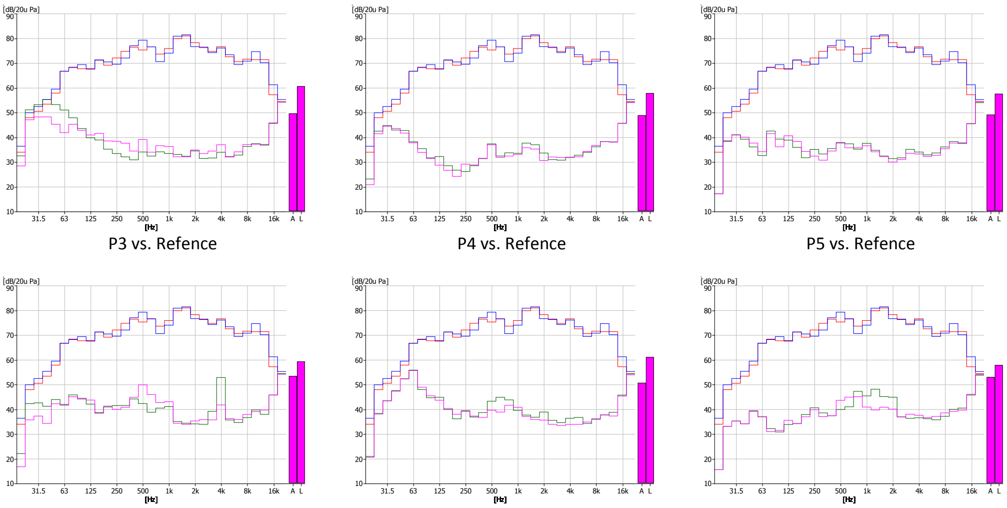
Reference point



P1 vs. Reference



P2 vs. Refence



P3 vs. Refence P4 vs. Refence P5 vs. Refence

P6 vs. Refence P7 vs. Refence P8 vs. Refence

Figure 9. Assessed levels from ESS recording at every point versus the reference point

Attenuation is calculated in every octave band with enough ESNR as the level in the reference point minus the level of the recording made in the point to be assessed. Two microphones were used in every recording, so their pressures will be energetically averaged to calculate the values displayed in Table 4.

Att. dB	P1	P2	P3	P4	P5	P6	P7	P8
20			-4,4				-14,5	
25	-5,5	-13,1	0,5	-7,0	-10,6	-8,9	-10,8	-15,9
31,5	-5,5	-14,1	-0,2	-7,0	-10,6	-10,9	-8,2	-16,3
40	-6,6	-15,1	-1,4	-11,2	-14,8	-15,5	-7,1	-20,3
50	-7,5	-16,9	-7,9	-16,5	-21,8	-15,6	-6,4	-19,4
63	-19,2	-30,3	-18,2	-28,7	-33,2	-24,9	-11,0	-29,7
80	-21,0	-32,2	-21,5	-33,5	-26,2	-22,8	-19,8	-36,6
100	-26,9	-34,3	-25,4	-37,0	-30,6	-24,3	-23,6	-37,4
125	-30,1	-33,9	-27,2	-36,8	-27,8	-24,6	-23,3	-32,9
160	-34,2	-36,9	-30,8	-43,5	-33,9	-32,7	-31,1	-37,0
200	-35,7	-37,4	-32,7	-44,2	-36,7	-28,7	-32,7	-32,4
250	-38,4	-37,7	-34,4	-43,1	-37,0	-30,2	-31,6	-30,8
315	-37,9	-42,2	-37,9	-44,9	-41,4	-32,4	-36,5	-35,7
400	-36,6	-43,4	-43,7	-45,3	-41,7	-32,2	-38,9	-39,3
500	-43,4	-43,9	-40,4	-40,6	-39,9	-30,1	-35,9	-35,6
630	-34,6	-39,8	-43,3	-44,4	-39,9	-32,9	-33,7	-33,2
800	-28,0	-37,1	-36,8	-39,3	-36,9	-30,6	-29,5	-26,1
1000	-32,0	-40,7	-39,9	-41,7	-37,9	-32,9	-34,8	-31,3
1250	-36,7	-48,0	-47,7	-43,6	-45,9	-45,7	-43,0	-34,7
1600	-39,5	-48,0	-49,0	-45,0	-48,9	-47,1	-44,8	-37,7
2000	-42,9	-45,8	-42,8	-45,1	-46,8	-42,8	-40,0	-34,4
2500	-31,5	-44,8	-43,8	-44,8	-45,0	-41,4	-41,6	-39,9
3150		-43,1	-41,2	-43,1	-40,1	-36,7	-40,4	-37,7
4000		-44,2	-40,6	-44,4	-42,7	-26,2	-41,0	-40,1
5000		-41,3	-41,3	-41,1	-40,4	-37,0	-37,4	-37,5
6300		-38,2	-38,3	-37,6	-38,7	-35,9	-36,1	-35,0
8000								
10000								

12500								-30,7
16000								
20000								

Table 4. Calculated attenuation, corrected by ESNR

Sound at the theatre (reference point) is recorded with a calibration reference and then analysed to extract A-weighted 1/3 Octave equivalent levels. The measurements correspond to the show on the night of August 16, 2016, which ends at 11:30 p.m.

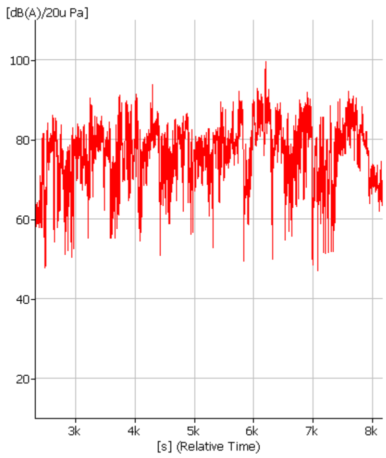


Figure 10. SPL versus time: A frequency-weighted and SLOW time-weighted

The moment with the highest SPL is around 6190 s after the beginning of the recording, in an instant when there is a tap-dancing together with the percussion. SPL exceeds 90 dBA in a few moments and the equivalent level is 80.3 dBA. As explained in 2.6, any descriptor can be calculated by post-processing.

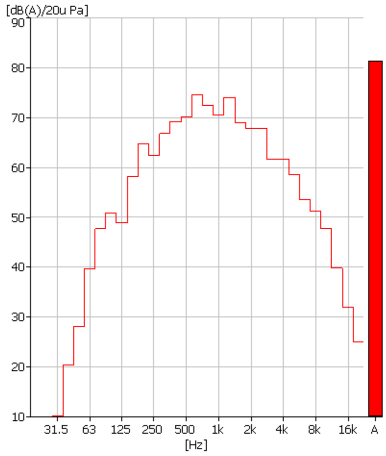


Figure 11. 1/3 octave-band Filtered A-weighted SPL (whole spectacle averaged)

The highest A-weighted sound levels in 1/3 octave bands are between 200 and 3150 Hz. Expected levels at the points of interest are calculated as the value in every band measured during the spectacle at the mixing desk (Figure 11) minus the attenuation corrected with ESNR (

Att. dB	P1	P2	P3	P4	P5	P6	P7	P8
20			-4,4				-14,5	
25	-5,5	-13,1	0,5	-7,0	-10,6	-8,9	-10,8	-15,9
31,5	-5,5	-14,1	-0,2	-7,0	-10,6	-10,9	-8,2	-16,3
40	-6,6	-15,1	-1,4	-11,2	-14,8	-15,5	-7,1	-20,3
50	-7,5	-16,9	-7,9	-16,5	-21,8	-15,6	-6,4	-19,4

63	-19,2	-30,3	-18,2	-28,7	-33,2	-24,9	-11,0	-29,7
80	-21,0	-32,2	-21,5	-33,5	-26,2	-22,8	-19,8	-36,6
100	-26,9	-34,3	-25,4	-37,0	-30,6	-24,3	-23,6	-37,4
125	-30,1	-33,9	-27,2	-36,8	-27,8	-24,6	-23,3	-32,9
160	-34,2	-36,9	-30,8	-43,5	-33,9	-32,7	-31,1	-37,0
200	-35,7	-37,4	-32,7	-44,2	-36,7	-28,7	-32,7	-32,4
250	-38,4	-37,7	-34,4	-43,1	-37,0	-30,2	-31,6	-30,8
315	-37,9	-42,2	-37,9	-44,9	-41,4	-32,4	-36,5	-35,7
400	-36,6	-43,4	-43,7	-45,3	-41,7	-32,2	-38,9	-39,3
500	-43,4	-43,9	-40,4	-40,6	-39,9	-30,1	-35,9	-35,6
630	-34,6	-39,8	-43,3	-44,4	-39,9	-32,9	-33,7	-33,2
800	-28,0	-37,1	-36,8	-39,3	-36,9	-30,6	-29,5	-26,1
1000	-32,0	-40,7	-39,9	-41,7	-37,9	-32,9	-34,8	-31,3
1250	-36,7	-48,0	-47,7	-43,6	-45,9	-45,7	-43,0	-34,7
1600	-39,5	-48,0	-49,0	-45,0	-48,9	-47,1	-44,8	-37,7
2000	-42,9	-45,8	-42,8	-45,1	-46,8	-42,8	-40,0	-34,4
2500	-31,5	-44,8	-43,8	-44,8	-45,0	-41,4	-41,6	-39,9
3150		-43,1	-41,2	-43,1	-40,1	-36,7	-40,4	-37,7
4000		-44,2	-40,6	-44,4	-42,7	-26,2	-41,0	-40,1
5000		-41,3	-41,3	-41,1	-40,4	-37,0	-37,4	-37,5
6300		-38,2	-38,3	-37,6	-38,7	-35,9	-36,1	-35,0
8000								
10000								
12500								-30,7
16000								
20000								

Table 4). Energetic addition of every band provides global SPL A-weighted values.

SPL, dBA	**P1**	**P2**	**P3**	**P4**	**P5**	**P6**	**P7**	**P8**
20			-2,8				-12,8	
25	1,3	-6,3	7,3	-0,2	-3,8	-2,1	-4,0	-9,1
31,5	4,7	-4,0	9,9	3,2	-0,5	-0,8	2,0	-6,2
40	13,7	5,2	18,9	9,1	5,5	4,9	13,3	0,0
50	20,7	11,3	20,2	11,6	6,4	12,6	21,7	8,7
63	20,5	9,4	21,5	11,0	6,5	14,8	28,8	10,0
80	26,7	15,6	26,2	14,2	21,5	24,9	27,9	11,1
100	24,0	16,6	25,5	13,9	20,2	26,5	27,3	13,4
125	18,8	15,0	21,7	12,1	21,1	24,3	25,6	16,0
160	24,0	21,3	27,4	14,7	24,3	25,5	27,1	21,2
200	29,1	27,4	32,1	20,6	28,1	36,1	32,1	32,4
250	24,0	24,8	28,0	19,4	25,4	32,3	30,8	31,7
315	29,0	24,6	28,9	21,9	25,4	34,4	30,3	31,1
400	32,6	25,8	25,5	23,9	27,5	37,0	30,3	29,9
500	26,8	26,3	29,7	29,6	30,2	40,0	34,3	34,6
630	40,0	34,8	31,3	30,2	34,7	41,8	40,9	41,4
800	44,4	35,3	35,6	33,1	35,5	41,8	42,8	46,3
1000	38,6	29,8	30,6	28,8	32,6	37,7	35,7	39,2
1250	37,4	26,1	26,3	30,5	28,1	28,4	31,1	39,4

1600	29,5	21,0	20,0	23,9	20,0	21,9	24,1	31,2
2000	24,9	22,0	25,0	22,7	21,1	25,0	27,9	33,4
2500	36,3	23,0	24,0	23,0	22,8	26,4	26,2	27,9
3150		18,6	20,5	18,5	21,6	25,0	21,3	24,0
4000		17,5	21,2	17,3	19,1	35,6	20,7	21,7
5000		17,2	17,2	17,4	18,2	21,5	21,1	21,1
6300		15,4	15,2	15,9	14,8	17,6	17,5	18,6
8000								
10000								
12500								-30,7
16000								
20000								
Global (dBA)	**47,8**	**40,3**	**41,4**	**38,7**	**41,2**	**48,2**	**46,9**	**49,4**

Table 5. Expected levels at the receiving points (A-weighted)

From a regulatory point of view, the most important place is the point with the highest estimated noise level. That is Point 8 (Cuesta del Rey Chico) with 49.4 dBA but it is a path in the vicinity of the theatre without residential buildings. The second one is Point 6 (near the Mosque) with 48.2 dBA. The measurement of the background noise was also very high (61.2 dBA). It must be highlighted that this point is 847 meters away from the PA as shown in Table 1. and there was a direct line of sight with the theatre, as shown in
Figure 12.

Point of interest	P1	P2	P3	P4	P5	P6	P7	P8
Lp Background (dBA)	60.0	62.3	50.4	49.7	54.7	61.2	59.9	57.6
Estimated Lp (dBA)	47.8	40.3	41.4	38.7	41.2	48.2	46.9	49.4

Table 6. Background noise (average of two channels) and estimated noise levels produced by the show

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shows that the expected noise levels produced by the concert are very much below the background noise. That is the main improvement of using the ESS method and would have been impossible to measure using sound level meters.

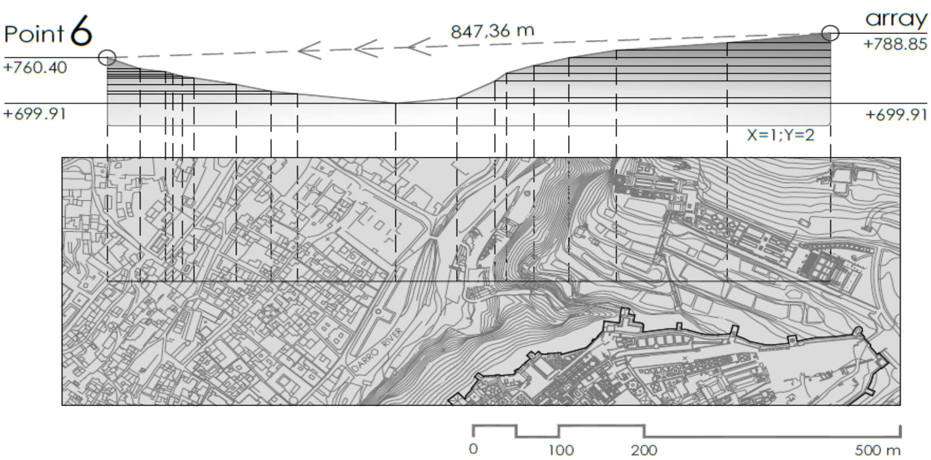

Figure 12. Elevation drawings of Point 6 sound path

There are some limitations of the method. As said in Section 3, assessing the quality of the computed impulse responses is not straightforward. The use of Schröder integral and different noise removal methods to choose the adequate time limits needs deeper research. Especially regarding the uncertainties derived from time limit decision.

The best way to minimize these uncertainties is by achieving good quality IRs. A good guide can be found in [24]. It recommends the usage of a wide-band sweep running up to the Nyquist frequency without any fade-out and the usage of a suitable “compacting” inverse filter, computed with the Kirkeby method from a “reference” impulse response to avoid pre-ringing artefacts. Also recommends a fade-in but in our case, the PA system low-frequency behaviour acts as a fade-in itself. It will also be interesting further research of IR skewing due to playback and recording digital clocks mismatch as has been commented on section 3. But probably the most hazardous situation to deal with the method is the presence of pulsive sounds. Pulsive sounds in the recorded sweeps are known to cause artefacts [24]. Figure 13 shows the spectrum of an IR which ESS record included pulsive noises (a person walking using flip-flops). A closer look at the computed IR spectrogram shows several down-sloping sweeps, overestimating the energy present at 1000 and 2000 Hz 1/3 octave bands.

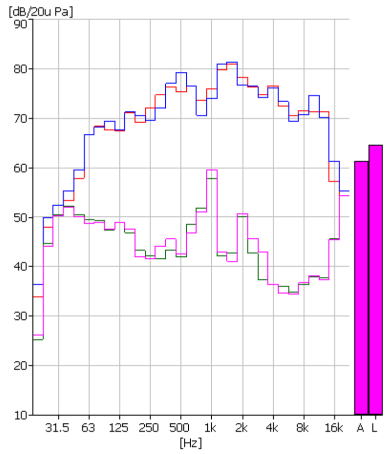

Figure 13. Artefacts induced by pulsive sounds at 1 and 2 kHz bands

Farina [24] offers different solutions but they are difficult to use when the energy of the pulsive noise is so high compared to the ESS. Using longer sweeps increase the possibilities of recording pulsive noises and the use of synchronous averaging of several sweeps would need further research. Pulsive events can be problematic even if the ESNR is good so repeatability of the results must be checked by recording several times in every point. The development of a criterion on the appropriate length of the ESS would help to achieve better results. Apart from the uncertainties due to the method, traditional sources of uncertainty [23], [43], [44], such as atmospheric conditions still play an important role in long-distance sound transmission. Wind, temperature, humidity changes and their inhomogeneities can cause the measurements not to be repeatable. Of course, the assessments made i.e. in the afternoon can have big differences with the actual levels of a spectacle held at night.

5. CONCLUSION

The described method is applicable in electroacoustic sources of noise and it is especially useful when the low signal-to-noise ratio impedes traditional methods to deliver reliable results. This method is valid when the ESNR is high enough to be assessed as in [37]. Also, the repeatability of the results must be checked to avoid errors caused by pulsive events. The improvements shown in this paper in terms of signal-to-noise ratio match with the claims of countless papers about the swept-sine method as [27], [37]. This case study shows its application in an open-air theatre but the method can be useful for different PA systems such as those for warning and evacuation messages, passenger stations, or freight terminals.

The selection of the receiving points is very important. This case study started with several complaints by neighbours but none of the measurements were made in their homes. It is feasible that the levels inside a house with a direct line of sight with the PA were higher and with lower background noise than street measurements.

The SPL produced by the theatre was several decibels below background noise (Table 6. Background noise (average of two channels) and estimated noise levels produced by the show

), therefore, it cannot be considered in terms of physical impact as it did not increase the noise exposure in Albaicín, and still, it was a cause of annoyance for the neighbours. Although this article deals with the assessment of objective parameters, such as SPL, it shows the importance of subjectivity in environmental noise assessment as explained in the introduction [10], [13]–[19]. Annoyance (%HA) grows with higher road traffic noise. It is common-sense and also shown i.e. in [2]. This case study shows the paradox of an audience in the theatre, exposed to 85 dBA, who are not likely to complain about noise and a group of neighbours in a far place, annoyed to hear music around 45 dBA in presence of 50 dBA of different noise.

6. ACKNOWLEDGEMENTS

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