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Caviedes Nozal, Diego; Heuchel, Franz Maria; Agerkvist, Finn T.; Brunskog, Jonas

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NOISE CONTROL FOR A BETTER ENVIRONMENT

The effect of atmospheric conditions on sound propagation and its impact on the outdoor sound field control

Caviedes-Nozal, Diego [1], Heuchel, Franz M.[2], Agerkvist, Finn and Brunskog, Jonas
Technical University of Denmark, Acoustic Technology Group
Ørsted Plads, Building 352, 2800 Kgs. Lyngby, Denmark

ABSTRACT

The performance of active sound field control solutions is directly dependent on the knowledge of the acoustic transfer functions between the control loudspeakers and control areas. Outdoors, the propagation of sound and thus these transfer functions are affected by atmospheric conditions and their variation. In this work we experimentally investigate the effect of wind and temperature changes on transfer functions. We present the results of a measurement campaign, where transfer functions and weather data were gathered every 30 minutes for a time period of a week. The results show the impact of wind (up to 8 m/s) and temperature (-2°C to 6°C) variations on the sound propagation over distances of around 300 m. We discuss the results in relation to the outdoor control of sound.

Keywords: Outdoor sound propagation, active control of sound
I-INCE Classification of Subject Number: 24
(see http://i-ince.org/files/data/classification.pdf)

1. INTRODUCTION

The propagation of sound in earth's atmosphere is a complex matter as it is highly influenced by the always changing wind and temperature conditions [1]. The design of any system that intents to synthesize a specific sound field outdoors, be it for the purpose of accurate reproduction of sound or its control, needs to be at least aware of such effects. With the final goal of designing a sound field control system for cancellation of sound from outdoor concerts [2, 3], we experimentally investigate in this work the impact of changes in atmospheric conditions on loudspeaker transfer functions measured at a far distance. The variability of transfer functions is a key factor in estimating the robustness and performance of static and adaptive sound field control systems.

The propagation of sound in complex media like the Earth's atmosphere is a well studied field (see e.g. [1] for a rigorous theoretical treatment). However, there have

[1] dicano@elektro.dtu.dk
[2] fmheu@elektro.dtu.dk

been only few experimental studies investigating the impact of short time-scale wind and temperature variations on sound propagation over medium scale distances ($\approx$ 200m). Such fluctuations might affect the accurately aligned destructive interference of waves on which the concept of active control of sound is based. A recent study by Cheinet et al. investigated the propagation of impulsive noise over distances of 50 m to 450 m in up-, down- and crosswinds [4]. For instance, they reported time-of-arrival fluctuations of up to 4 ms over 300 m at a down-wind of 3 m/s. Such a change would lead to perfect constructive interference instead of destructive cancellation at a frequency of 125 Hz. To obtain a sound pressure level reduction of 10 dB at the same frequency, the time-of-arrival may not vary more than 0.5 ms assuming zero variations in the impulse gain [5, p. 15].

While Cheinet's study thoroughly investigates the fluctuations of impulses, it does not compare them to the fluctuations of atmospheric conditions like wind and temperature. The current work wants to shed at least some light on this link. We present experiments of transfer-function measurements over medium large distances in a variety of wind conditions and compare their fluctuations with measurements of the atmospheric conditions. In addition, we validate the linear-logarithmic sound speed profile model to the measured results based on [6], as a preparatory step to model the outdoor sound propagation in future work.

2. THEORY

2.1. Sound propagation in inhomogeneous media

Modeling outdoor sound propagation is a challenging problem because the atmosphere is a moving medium due to temperature and wind. A common approximation is to assume that the sound is propagating through an effective, motionless medium characterized by its effective speed of sound

$$c_{eff} = c + \mathbf{v} \cdot \mathbf{n}, \tag{1}$$

where $\mathbf{v}$ is the wind vector and $\mathbf{n}$ is the direction of sound propagation. The scalar c is the adiabatic speed of sound

$$c = \sqrt{\gamma \mathrm{R} T} \simeq 20.05\sqrt{T} \quad [\mathrm{m/s}], \tag{2}$$

where $\gamma \simeq 1.4$ is the adiabatic index, $\mathrm{R} \simeq 287\,\mathrm{J\,kg^{-1}\,K^{-1}}$ is the gas constant of air and T is the temperature in K.
For sound propagation near the ground where the angle of $\mathbf{n}$ to the ground is small Equation 1 is written

$$c_{eff} = c + v\cos\theta, \tag{3}$$

where v is the horizontal component of the wind and θ is the angle between the azimuthal direction of sound propagation and the horizontal wind component. With a flat homogeneous ground, temperature and wind can be considered to vary only as functions of height z and the speed of sound is $c_{eff}(z) = c(z) + v(z)\cos\theta$ [7]. Measuring both wind and temperature at sufficient vertical resolution can be troublesome but there exist sound

speed profile models that can be applied to estimate Eq. (1). A realistic profile of the speed of sound in the atmospheric surface layer is a logarithmic-linear profile [6, 8]

$$c_{eff}(z) = c_0 + a \log\left(\frac{z}{z_0}\right) + bz, \tag{4}$$

where c_0 is the speed of sound at ground level, z_0 is the roughness height and a and b are constants dependent on wind and temperature that can be calculated by means of Monin-Obukhov similarity theory [8, 9].

2.2. Active cancellation of sound

The sound from a primary loudspeaker source can be cancelled by a secondary control loudspeaker. In frequency domain and assuming time invariance, let $P(\mathrm{j}\omega)$ and $C(\mathrm{j}\omega)$ be the primary and secondary path transfer functions to the cancellation point, $S(\omega)$ be the excitation signal, $H(\mathrm{j}\omega)$ be the control filter that is applied to the excitation signal before it is fed to the control loudspeaker and $N_e(\omega)$ be background noise at the control point. The signal at the control point is then

$$E(\omega) = P(\mathrm{j}\omega)S(\omega) + H(\mathrm{j}\omega)C(\mathrm{j}\omega)S(\omega) + N_e(\omega).$$

The optimal, unconstrained control filter is $H_{opt}(\mathrm{j}\omega) = -P(\mathrm{j}\omega)/C(\mathrm{j}\omega)$ if the same signal feeds both primary and control loudspeakers [5, p. 176].

In practice, the maximum achievable reduction in sound pressure level (SPL) at the control microphone is limited by the background noise and the accuracy of the control filter. In order to produce a 10 dB reduction in SPL in the absence of noise, the control filters must not deviate either more than ±2.5 dB or ±20° from the optimal filter [5, p. 15].

Adaptive filtering methods like the filtered-x Least-Mean-Square (FxLMS) algorithm are often used in active control applications to estimate the optimal control filter continuously in real-time when there are fluctuations in the primary or secondary path. The FxLMS algorithm converges for slow variations of the primary path, if the phase difference between the actual and previously estimated secondary path does not exceed 90°. Differences below 45° only have a small influence on the convergence speed [10].

These limits will help us to evaluate the variations of transfer functions due to weather conditions in the following sections.

3. EXPERIMENTAL SETUP

We investigated the influence of weather on sound propagation by measuring transfer functions between two sub-woofers (LS1, LS2) and four pairs of microphones (M1-M8) separated by 170 m-300 m of flat grassy meadow, see Fig. 1. For 5 days, from 8 am to 5:30 pm, transfer functions were measured every 30 minutes from both sources separately (LS1, LS2) and jointly (LS1+LS2). Each of these four measurements consisted of 10 repetitions of a 10 s exponential sine sweep.

Wind direction, wind speed and temperature were recorded at a weather station in between the loudspeakers and microphones at 18, 31, 44, 57 and 70 meters with an additional temperature and humidity sensor at 2 m above ground.

The subwoofers had a nominal frequency range of (37 - 115 Hz, -5 dB).

Figure 1: Experimental setup at the Risø campus wind park of the Technical University of Denmark. Left: position of loudspeakers, microphones and weather station. Middle: pair of microphones M3, M4. Right: loudspeaker LS1 and weather mast.

4. DATA SUMMARY

4.1. Weather

The weather conditions during the measurements are summarized in this section. Figure 2 (a) shows the temperature at 2, 18, 31, 44, 57 and 70 m over time. The temperature range during the 6 days varies approximately between -4 and 4 °C at 2 m. Figure 2 (b) shows the wind direction and speed at 18 m, with a higher concentration of wind coming from the North-East with wind speeds up to 8 m/s. This trend is similar to all the measured heights (not shown in the figure).

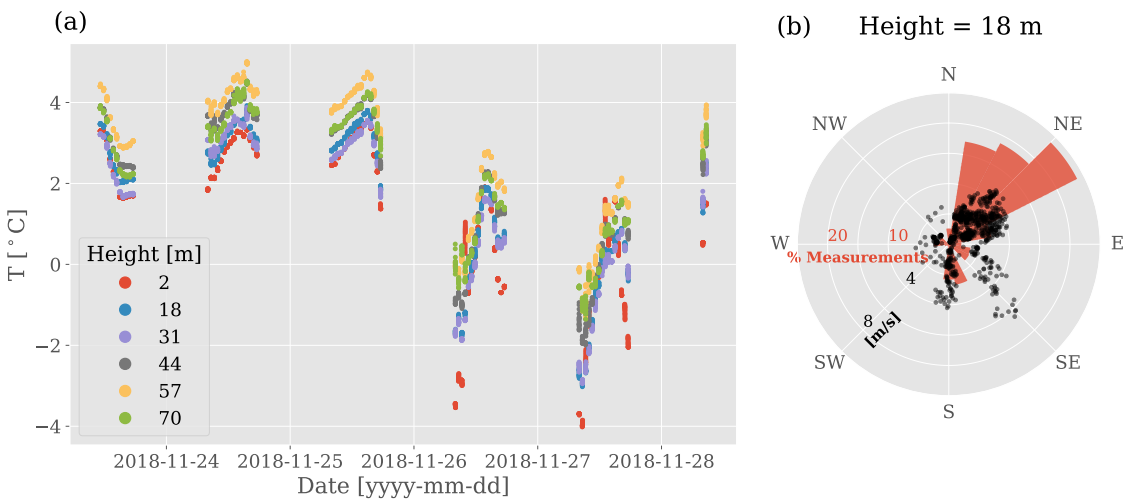

Figure 2: Temperature and wind at the transfer function recording times. (a): Temperature over time at different heights. (b): Wind at 18 m. In red the histogram of wind directions. In black the speed and direction of each measurements.

Temperature and wind speed profiles are shown in Fig. 3 (a) and (b) respectively. Temperature profile shows an increasing temperature at heights between (2-18) and (31-57) m and temperature inversion between (18-31) and (57-70) m. Even though

temperature inversion is a common meteorological effect, sensor mismatch can be also its cause. The wind speed increases with height for most of the cases.

4.2. Sound speed profile

We calculated the sound speed profile using the logged wind and temperature at heights of 18, 31, 44, 57 and 70 m in Eq. (1). In order to verify the accuracy of the logarithmic-linear profile, we fitted the model in Eq. (4) to the calculated sound speed profile.
The mean squared error between the calculated and the modelled profile is shown in Fig. 3 as black dots. It can be seen that the error is below 0.2 for most of the cases. At day 2018-11-26 there are some outliers where the error is higher than 1. This behavior can be related with the results seen in Fig. 2 where the temperature stratification shows a more complex pattern.
In the same figure, shown in red dots is the difference between the calculated speed of sound at ground level where no wind is considered and the fitted parameter c_0 from Eq. (4). We can observe large differences of ±20 m/s, showing again outliers the 2018-11-26. These results show a bad extrapolation of the model at lower heights.

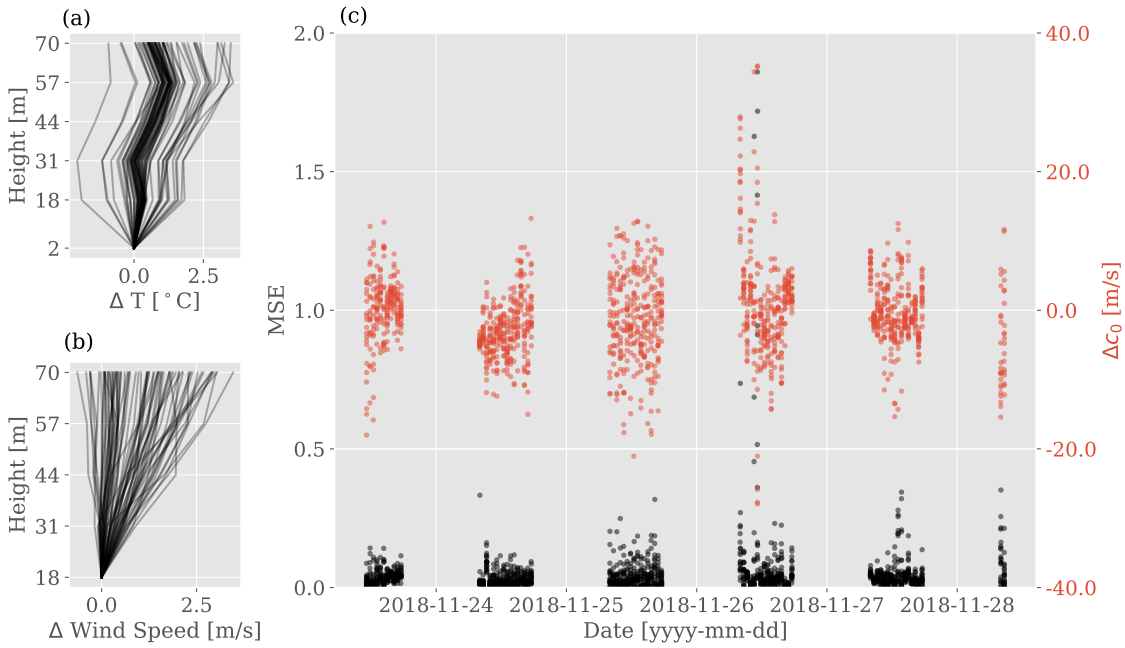

Figure 3: (a): Measured temperature profiles normalized to T_{2m}. (b): Measured wind speed profiles normalized to wind at 2 m. (c) Black: Mean squared error (MSE) between the calculated c_{eff} profiles in Equation 1 and the model in Equation 4 for heights from 18 to 70 m. Red: Deviation between the parameter c_0 in Equation 4 and the adiabatic speed of sound at 2 m.

4.3. Signal to noise ratio

The average signal-to-noise ratio (SNR) to the furthest microphone during the measurement campaign was above 16 dB for LS1 and above 20 dB for LS2 (see Fig. 4 left). Placing the microphones on the floor gave a slighlty better SNR ratio in windy conditions compared to the microphone at 1 m height. At low wind speeds however, the

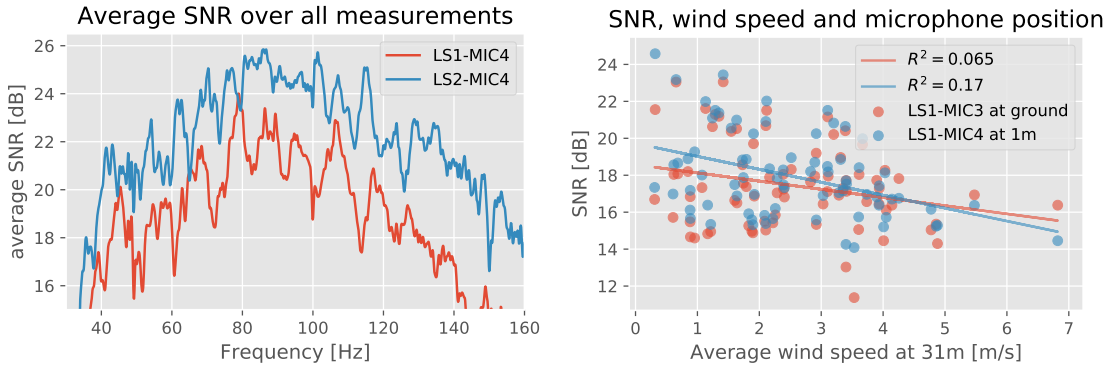

Figure 4: Left: average signal-to-noise ratio in sine sweep measurements between the two loudspeakers and the furthest microphone (4). Right: signal to noise ratio vs average wind speed for measurement of loudspeaker 1 to microphones 3 and 4.

lower position gave slightly less SNR, probably due to some shadowing from the ground and its vegetation.

5. SOUND AND WEATHER

Section 2.1 briefly described how flow in a moving medium and temperature variations change the local speed of sound. An increase in the speed of sound in homogeneous conditions, i.e. no stratification of the atmosphere, will result in sound arriving more quickly, i.e. the impulse response shifts in time. In general, one would expect the distortion of the impulse response to be rather complex due to the inhomogeneous wind and temperature distribution in the atmosphere.

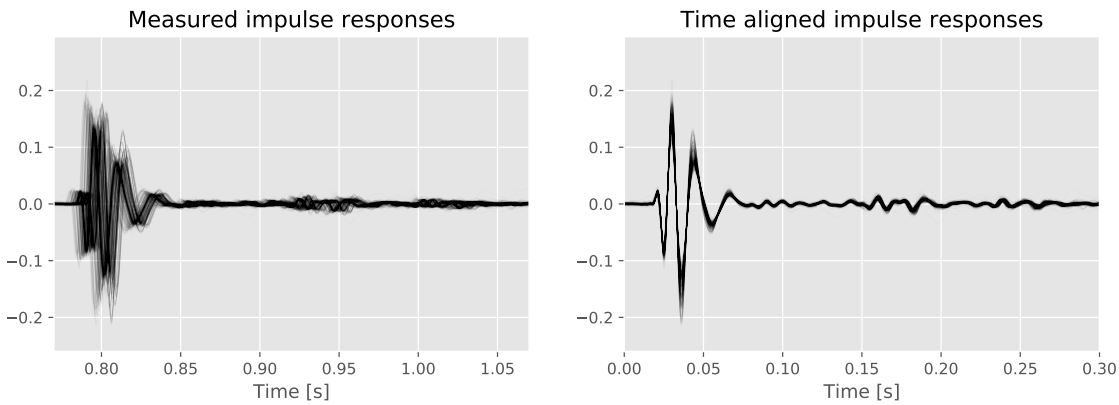

Figure 5: Left: 770 measured impulse responses between LS2 and M4. Right: time aligning the impulse responses reveals that they have very similar shape.

Figure 5 shows all measured impulse responses between LS2 and M4. The frequency responses vary in magnitude by up to ±5 dB over the frequency range of the subwoofer (Fig. 5 left). The phase variations can be up to several cycles, depending on the frequency. A static sound field control system will not work effectively in a similar range of weather conditions. Time aligning the impulse responses to the first measured response by means of maximum cross correlation reveals that the responses have very similar shape (Fig. 5 right). Interestingly, the phase variation in comparison to the first impulse response

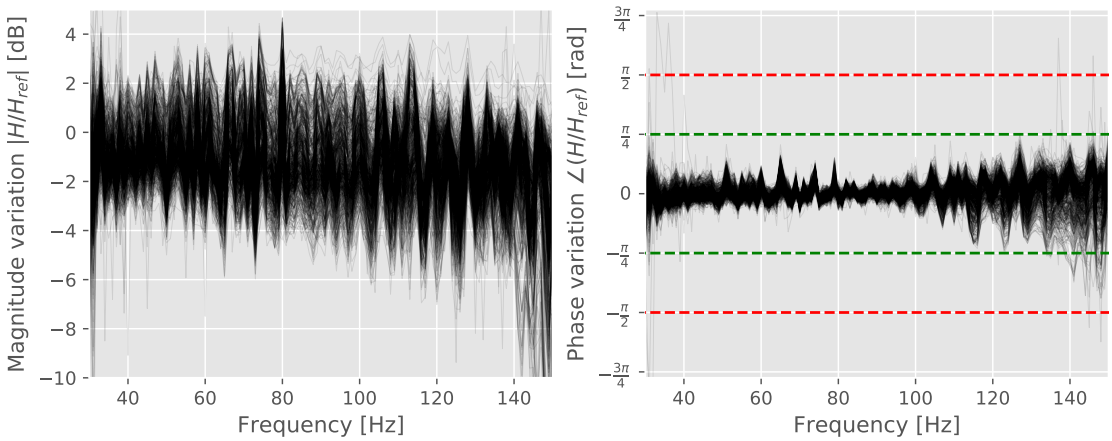

Figure 6: Magnitude (left) and phase variations (right) of time aligned impulse responses relative to the first measured impulse response.

is, once time aligned, lower than 45° in the whole frequency range of the subwoofer (Fig. 6 right). This suggests that an FxLMS algorithm that has LS2-M4 as its secondary path could work efficiently, as long as the delay introduced by the weather variations is accounted for in the internal secondary path estimate.

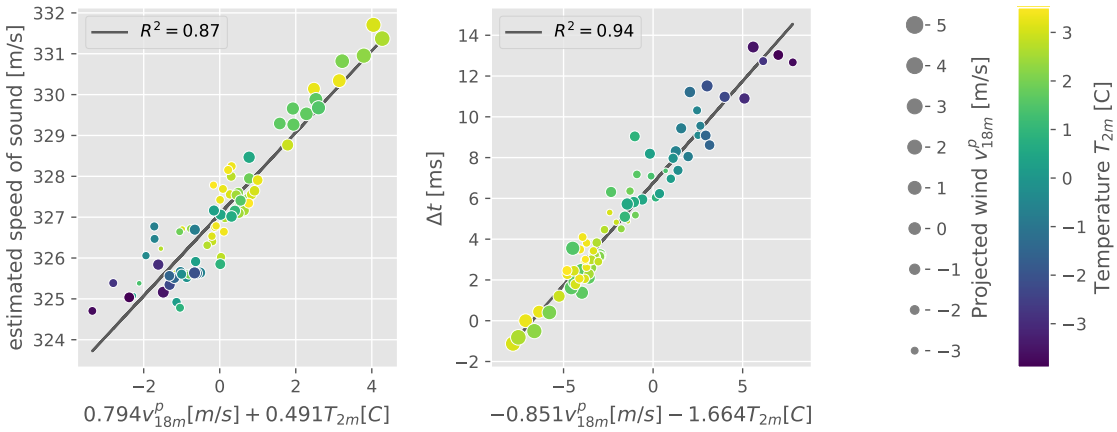

Figure 7: Measured speed of sound and delay of impulse response between LS2 and M4 as a function of projected wind and temperature.

The shift in delay Δt of each response relative to the first response, averaged over 10 repetitions, is compared to the ambient temperature at 2 m and the wind speed at 18 m in Fig. 7 (right). The wind speed is projected onto the direction of sound propagation between LS2 and M4, as this component of the wind vector will have the largest influence onto the speed of sound according to Eq. (1). The general distribution of delay changes is well modelled by a linear combination of temperature and projected wind speed. However, the linear model does not explain all the variation in the data. Some delays deviate more than 1 ms from the model. This suggests that it is unlikely that such a simple model is accurate enough to be used to estimate the delay variation in the secondary path model of an FxLMS algorithm by just measuring the projected wind and temperature.

We estimate the instantaneous effective speed of sound in two ways with the LS1+LS2 measurement: 1) measuring the arrival difference between microphones M3,4 and M7,8

and 2) measuring the time difference between the impulses belonging to loudspeakers LS1 and LS2. Figure 7 shows the average over both of these estimates as a function of projected wind speed and temperature. Note that we assume here a homogeneous speed of sound in the whole area of the experiment. The overall behaviour of the estimated speed of sound can be approximately explained by a linear regression model of the near ground temperature and the projected wind speed at 18 m. However, the parameters of this regression model

$$c = (327.1 \pm 0.1) + (0.79 \pm 0.05)v_{18m}^{projected} + (0.49 \pm 0.05)T_{2m}$$

do not match well with a first order approximation of an homogeneous effective speed of sound (Eqs. (1) and (2))

$$c \approx 331.4 + v^{projected} + 0.6T.$$

One will probably have to use a more refined model that includes temperature and wind gradients to explain the measured speed of sound in this experiment.

6. CONCLUSIONS

This work experimentally investigated the variation of transfer functions due to changing weather conditions. For the weather conditions and setup of the experiment, we showed that the transfer functions have only small phase variations below 45° when compensated by an appropriate delay. This suggests that it could be sufficient to update the secondary path model in an adpative FxLMS algorithm by changing a delay only. While one can model such a delay approximately with a linear model as a function of wind and temperature, it is questionable if such an estimate is accurate enough for the estimation of the delay in the above application.

We also compared the logarithmic-linear model of speed of sound to an estimate based on measured wind speed and temperature at different heights showing large deviations in some conditions. It is the goal of future work to investigate the influences of these deviations on the applicability of this model for accurate outdoor sound propagation estimation.

The weather and sound data gathered in this experiment is available to fellow researchers under reasonable request.

7. ACKNOWLEDGEMENTS

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