Spatial Focusing of Time-Reversed UWB Electromagnetic Waves in a Hallway Environment

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***Abstract*— Spatial Focusing of Time-Reversed UWB Electromagnetic Waves is demonstrated in a Hallway Environment. A general time domain channel model for pure reflection environment like hallway has been built. This model is easily to be implemented with Matlab. Based on this model, simulation results shows 10dB down when the receiver is 1m away from the intended receiver.**

I. INTRODUCTION

Ultra-wideband wireless communications techniques have many attractive characteristics, including an extremely simple radio that inherently leads to low-cost design, and fine time resolution for accurate position sensing. However, there are a number of challenges in UWB receiver design, such as capturing multipath energy, intersymbol interference and co-channel interference. A Time-Reversal (TR) technique has been applied to solve these problems [1]

The irreversibility of time is a topic generally associated with fundamental physics [2]. The object is to exploit TR invariance, a fundamental symmetry that holds everywhere in fundamental particle physics to create useful systems. What one wants is macroscopic time-reversal invariance. Happily this symmetry does hold in both acoustic-wave and electromagnetic-wave phenomena. Due to the high resolution of a short UWB pulse, rich resolvable multipath makes the UWB channel act like an underwater acoustical channel. The success of using time reversal for underwater acoustical communications motivates this paper.

In a TR communication system, after the intended receiver sounds the channel by transmitting a pilot sequence to the transmitters, the transmitters record, time-reverse and then retransmit the time reversed signal back to the channel. As a result, the energy will be focused in both the time and the space at the intended receiver. TR has been studied for a long time in acoustic [2] and extended to wireless communication recently [3].

The complexity of realizing TR is one of concerns in TR implementation. The fact that TR technique uses the channel itself as the matched filter enable the low complexity of the system. It is interesting to know that sampling the CIR and using reduced-bit A/D conversion can be as good as full rate and normal-resolution (8 bits) A/D approach [4]. Some implementation schemes have been reported recently in [5].

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In this paper, the spatial focusing of time-reversed UWB electromagnetic waves in a hallway environment has been investigated. We first derive a closed form impulse response of the hallway environment in 2D, based on the powerful ray tracing technique. Image theory has been employed to do the ray tracing. The impulse response derived in this paper is different from that of previous work, e.g., the work in [6][7][12], in the following aspects. First, the closed form impulse response has been given in time domain directly; Secondly, the impulse response derived in this paper is more general because it takes into account the materials of the environment as well as its geometric configuration. Moreover, this model can be easily generalized to 3D case.

Based on the derived impulse response, the spatial focusing of TR has been demonstrated by simulation. The results show that there is 10dB energy drop down when the receiver is 1 m away from the intended receiver.

The remainder of this paper is organized as follows: In Section II, spatial focusing and the corresponding formulation used in following the simulation has been presented. A general time domain channel model for the hallway environment was built in Section III. Based on this channel model, we study the spatial focusing of the TR technique. Some of interesting numerical results were presented in Section IV. Conclusions are drawn in Section V.

II. SPATIAL FOCUSING OF TIME REVERSAL

Three main benefits can be achieved by employing TR technique in a communication system. These benefits are, temporal focusing, spatial focusing and hardening of the effective channel [8]. In this paper, we only focus on the spatial focusing. Spatial focusing near the intended receiver has many important applications. For example, co-channel interference in a multi-user systems can be greatly reduced by increasing the spatial focusing of the system. In military applications, increasing the spatial focusing is a very efficient way to deal with the interception. In this sense, TR technique can exploit multipath to create a secure communication channel with a receiver at a particular location.

Consider a TR system with single input and single output antenna(SISO). Let $h(\vec{r}_0,t)$ represents the impulse response of the channel when the receiver locates in position $\vec{r}_0(x_0,y_0,z_0)$. The transmitter will use the complex conjugate of the time reversed version of $h(\vec{r}_0,t)$ as the prefilter. Similarly, let $h(\vec{r}_1,t)$ denotes the channel impulse response of another unintended user at position $\vec{r}_1$. Assuming channel is reciprocal and slowly varying, which is the case for UWB signal [9], the equivalent channel impulse response(CIR) for the intended user would be

$$h_{eq}(\vec{r}_0,t) = h(\vec{r}_0,-t) * h_(\vec{r}_0,t) \quad (1)$$

where $*$ represents convolution operation. For the unintended user, the equivalent CIR would be

$$h_{eq}(\vec{r}_1,t) = h(\vec{r}_0,-t) * h(\vec{r}_1,t) \quad (2)$$

The spatial focusing can be characterized by the metric Directivity $D(\vec{r}_0,\vec{r}_1)$, which is defined as

$$D(\vec{r}_0,\vec{r}_1) = \frac{max\left|h_{eq}(\vec{r}_0,t)\right|^2}{max\left|h_{eq}(\vec{r}_1,t)\right|^2} \quad (3)$$

The value of Directivity $D(\vec{r}_0,\vec{r}_1)$ determines how well we can, by employing TR, focus the transmitted energy into a point of interest. Similar metric has been used in measurement paper [8] to characterize the spatial focusing of TR system. In the following paper, we will investigate this parameter by moving the receiver away from the intended focusing point and studying how fast the receiving energy will drop down.

III. Time domain modeling wideband radio propagation in the hallway

Hallway is a special indoor environment in the sense of its long and relative narrow geometric configuration. In a hallway environment, multiple reflection rays, together with the Light of Sight(LOS) ray, will dominate the received signal. Theoretically, radio propagation in a hallway can be modeled as a tunnel propagation problem, which has been investigated intensively over the past decades. Two approaches have been employed to model the radio propagation in tunnels. One is modal approach [6], and the other one is ray approach [11][12]. In a tunnel whose size is very large relative to wavelength, which is the case for the analysis of UWB signal propagation in a hallway, the ray model, should be more accurate and simpler.

Ray tracing is a very powerful method to model the wireless channel at high frequencies when the entire geometry of the environment is taken into account. This technique will be employed to built our propagation model. Moreover, due to the transient characteristics of UWB pulses, it should be more convenient to analyze the UWB signals in the time domain directly. That's the motivation of our time domain propagation model.

Specular reflection is assumed for all the reflections undergoing in the hallway environment. This is a reasonable assumption considering the roughness of the walls are far less than the wavelength of the propagation signal. We also assume all the reflection interfaces (ceiling, floor, and two side walls) are made of the same material with a relative dielectric constant ε_r.

We first consider a two-dimension model, and then extend the result to three dimension environment. The physical configuration of two-dimensional hallway modeling is shown in Fig. 1. Image theory is employed in the ray tracing. According to image theory, all the rays can be viewed as coming from the multiple images of source S_0. These rays can be divided into two categories; one is that the first reflection happens in the floor, the other one is that the first reflection happens in the roof. It should be noted that these two cases have common laws. Firstly, our interest will focus on the case 1, the first reflection happen in the floor. We will show that this model, although established based on case 1, is suited to case 2 as well.

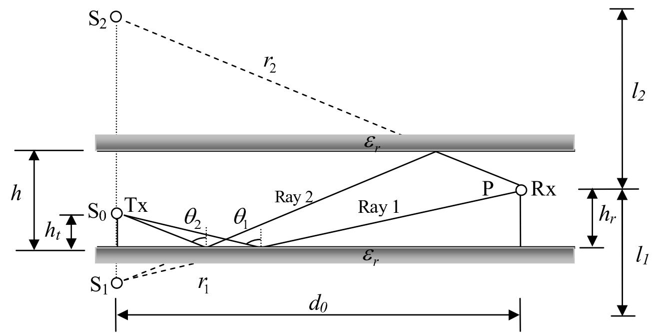


Fig. 1. The physical configuration of two-dimensional hallway modeling: all the multipath can be viewed as coming from the images of source S_0.

Fig. 1 shows the first and the second ray (corresponding ray1 and ray2 in Fig. 1) that the first reflection happens in the floor. In Fig. 1, S_1 is the image of S_0 relative to the floor, while S_2 is the image of S_1 relative to the ceiling. Viewed from the receiver, ray1 and ray2 seem coming from image S_1, S_2 , respectively.

The electric field of a ray arriving at the receiving antenna can be calculated by the following equations.

For the direct ray, which is LOS path,

$$E_{Direct}(f) = \frac{E_0}{r}e^{-jkr} \quad (4)$$

where E_0 is the electric field transmitted by the antenna, k is the wave number and r is the distance that the ray travels from the transmitter to the receiver.

For reflected rays,

$$E_{reflected}(f) = \Gamma\frac{E_0}{r}e^{-jkr} \quad (5)$$

where $\Gamma = \prod_{i=1}^{n}\Gamma(\theta^i)$ is the accumulated reflection coefficient. Here, n represents the number of reflections undergone by the ray, and θ^i is the corresponding reflection angle. Since the ceiling and the floor are parallel, equal reflection angle will be assumed for the same ray undergoing multiple reflections. For example, ray2 in the Fig. 1 has the same reflection angle θ_2 for the two reflections. Therefore, we can simplify the equation (5) as: $\Gamma = \prod_{i=1}^{n}\Gamma(\theta^i) = [\Gamma(\theta)]^n$.

It's known that reflection coefficient $\Gamma(\theta)$ is frequency dependent. Calculation of $\Gamma(\theta)$ for UWB signal in the time domain has been well studied in [13]. For early time-response, the impulse response of reflection can be approximated as [13]:

$$h_{ref}(t) \approx K\left\{\delta(t) + \frac{2a\kappa}{1-\kappa^2}exp[-(1+K)at]\right\}U(t) \quad (6)$$

where $K = (1-\kappa)/(1+\kappa)$, and $a = 60\pi\sigma c/\varepsilon_r$. Here, c is the speed of light, σ is the conductivity of the reflection surface, $\kappa = \sqrt{\varepsilon_r - sin^2\theta}/(\varepsilon_r cos\theta)$ for vertical polarization and $\kappa = cos\theta/\sqrt{\varepsilon_r - sin^2\theta}$ for horizontal polarization. Notice that the reflection signal consists of two parts: One is undistorted signal corresponding to the delta function in (6), and the other one is distorted signal corresponding to the second term in (6). The simulation results in [13] show that the contribution from the second term is very small thus can be ignored in a typical reflection situation. In this case, equation (6) could be simplified as: $h_{ref}(t) \approx K\delta(t)$. After some mathematic manipulations, the parameter k can be reformed as:

$$K_{H,V} = \frac{\cos\theta - a_{H,V}\sqrt{\varepsilon_r - \sin^2\theta}}{\cos\theta + a_{H,V}\sqrt{\varepsilon_r - \sin^2\theta}} \quad (7)$$

where $a_H = 1$, $a_V = 1/\varepsilon_r$ and "H" and "V" correspond, respectively, to the horizontal and vertical polarizations. Therefore, (6) naturally reduces to traditional Fresnel reflection coefficient, which is frequency independent. This give us confidence to use the frequency independent reflection coefficient, despite the wide band characteristics of UWB signal. Thus we have

$$\Gamma_{H,V}(\theta) = \frac{\cos\theta - a_{H,V}\sqrt{\varepsilon_r - \sin^2\theta}}{\cos\theta + a_{H,V}\sqrt{\varepsilon_r - \sin^2\theta}} \quad (8)$$

For different rays, reflection angle θ is different. It should be noted that θ is closely related to the number of the reflections that the ray has experienced. Let θ_n denote the reflection angle for the nth ray, which is the ray with reflection time of n, then θ_n can be calculated by the triangle relationship

$$\theta_n = \arcsin(\frac{d_0}{r_n}) \quad (9)$$

where d_0 is the antenna separation distance and r_n is the distance that the ray propagates. Note that $r_n = \sqrt{l_n^2 + d_0^2}$, where l_n is the vertical distance between the image S_n and the receiver. The distance l_1, l_2 and d_0 are shown in Fig. 1. l_n can be further calculated by the following equation:

$$l_n = \begin{cases} (h_t + h_r) + 2h(n-1) & n \text{ is odd} \\ (h_t - h_r) + 2hn & n \text{ is even} \end{cases} \quad (10)$$

where, as shown in Fig. 1, h_t, h_r and h represent the height of transmitting antenna, receiving antenna and the hallway, respectively. The total received electric field in the receiver can be expressed as

$$E(f) = \sum_{n=1}^{N} [\Gamma(\theta_n)]^n \frac{E_0}{r_n} e^{-jkr_n} \quad (11)$$

Let $H(f)$ be the channel transfer function, which is defined by $H(f) = E(f)/E_0$, then we have

$$H(f) = \sum_{n=1}^{N} [\Gamma(\theta_n)]^n \frac{1}{r_n} e^{-jkr_n} \quad (12)$$

For the wideband signal such as UWB pulse, it is believed that efficiency will be achieved by analyzing the signal

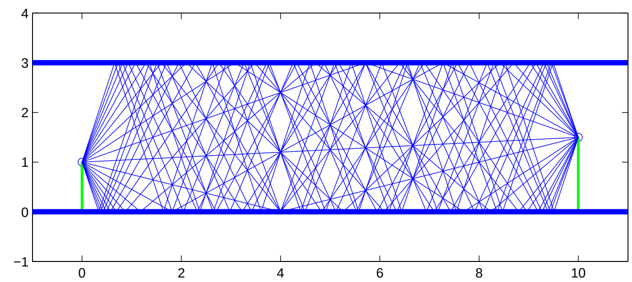


Fig. 2. Ray tracing result in the hallway. Ten times reflection rays for each reflection interface has been traced ($N = 10$).

directly in the time domain. Taking Inverse Fast Fourier Transform(IFFT) on (12), the impulse response can be expressed as

$$h(t) = \sum_{n=1}^{N} [\Gamma(\theta_n)]^n \frac{1}{r_n} \delta(t - \frac{r_n}{c}) \quad (13)$$

Note that the general channel model without distortion is $h(t) = \sum_{n=1}^{N} a_n \delta(t - t_n)$, where a_n is the amplitude attenuation and t_n is the time delay. Time domain model given in (13) can be reduced to general channel model with $a_n = \Gamma^n(\theta_n)/r_n$, and delay $t_n = \frac{r_n}{c}$.

Theoretically, we can trace infinite number of multipath with the equation (13), however, only limited number of them, will be meaningful. The reason is that the energy of the signal decreases very fast due to the energy loss caused by reflection and free space propagation.

So far, we only consider the contribution from the rays that first reflection happen on the floor. Similar analysis can be applied to those rays that first reflection happen on the other interfaces. For example, if we rotate Fig. 1 180 degree so that the positions of roof and floor are exchanged, while keeping the position of antenna fixed, (13) will be the contribution from those rays that the first reflection happen on the roof. In this case, h_t and h_r in (10) will be the distance from corresponding antenna to the roof. If we rotate Fig. 1 90 degree, one of the side walls will become the floor. The antenna height h_t and h_r in (10) then will be replaced by the distance between the antenna and the corresponding side walls.

Fig. 2 shows the retracing result in 2D case. This result shows that the reflection rays that the first reflection happened in the floor, as well as those that happened in the ceiling. The parameter used in the simulation is as follows: $h_t = 1m$, $h_r = 1.4m$, the height of the hallway $h = 3m$, the distance between two antennas $d_0 = 10m$ and the maximum multipath number traced in every reflection interface $N = 10$.

Considering the ray from all the four interfaces, the impulse response of the hallway in 3D case can be modeled as:

$$h(t) = \sum_{m=1}^{4} \sum_{n=1}^{N} [\Gamma_m(\theta_{mn})]^n \frac{1}{r_{mn}} \delta(t - \frac{r_{mn}}{c}) \quad (14)$$

where θ_{mn} and r_{mn} can be calculated by (9) and (10), with the corresponding parameters.

Equation (14) is a very general time domain channel model for hallway environment. Given the coordinates of the Tx and Rx, as well as the geometric parameters of the environment, all the multipath can be retraced with this model.

It should be noticed that the model given in this paper ignores the impact of antennas. Generally Antennas play very important role in UWB communication systems. However, since the transmitter and receiver antennas can be as a whole modeled as a linear filter with impulse response $h_a(t)$, their impact can always be absorbed in the new transmitted pulse waveforms [14].

Fig. 3 shows the retracing result in 3D case. The transmitter antenna locates in position $(0,0.5,1.5)$ and the receiver antenna locates in position $(10,1.1,1)$. Maximum multipath number traced in each reflection interfaces $N=3$. The width of the hallways is $3m$. The rest of parameters are the same to 2D case.

IV. Numerical results

In a TR communication system, firstly the receiver will send a pulse to sound the channel. In our simulation, the second order derivative of Gaussian pulse has been used as sounding pulse, which, mathematically can be defined as:

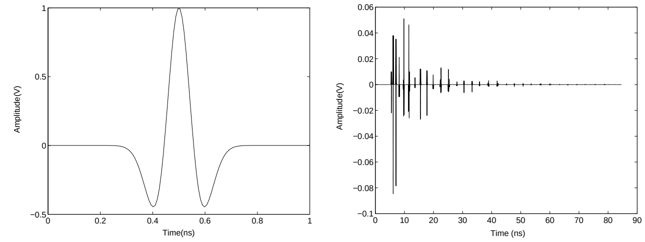
$$s(t) = \left[1 - 4\pi\left(\frac{t-t_c}{w}\right)^2\right] e^{-2\pi\left(\frac{t-t_c}{w}\right)^2} \qquad (15)$$

where w is the parameter used to control the width of the pulse and t_c is time shift to put the pulse in the middle of the window. Fig. 4(a) shows the sounding pulse with $w=0.2ns$ and $t_c=0.5ns$. After the pulse passes through the channel, which has been described in Fig. 3, the receiving signal in the transmitter was shown in Fig. 4(b). It should be noted that we manually block the LOS path to avoid the dominated path in the receiving signal. Since the sounding pulse is very short, we can treat the result in Fig. 4(b) as the impulse response of the channel. Then the transmitter will adopt the time reversed of the channel impulse response, denoted by $h(\vec{r}_0,-t)$, as prefilter.

To simplify the problem, we restricted the moving range of the receiver only in the direction of $\vec{r}_0$. Under this condition, the problem reduces to one dimension case. $D(\vec{r}_0,\vec{r}_1)$ then can be reformed as $D(d_0,d)$, where d is the separation distance between the transmitter and the receiver and d_0 is the the distance of our focusing point.

Fig. 5 shows the equivalent CIR, which is defined in section II, for different users. Fig. 5(a) shows the equivalent CIR for the intended user located at $d_0=10m$, while Fig. 5(b) gives the equivalent CIR of the undesired user located at $d=11m$. It's evident that the power received by intended user will be much stronger than the unintended user, hence, spacial focusing is achieved by employing TR technique.

Let $d_0=10m$, we move the receiver away from the intended focusing point, with a step of $0.2m$. Fig. 6(a) shows how the parameter $D(d_0,d)$ change with the distance d. It's observed in Fig. 6(a) that there is a peak at distance d_0 and then $D(d_0,d)$ decays rapidly when the receiver is away from d_0. It's known that, due to the energy loss caused by free space propagation, the receiving power will drop down when the receiver moving far from the transmitter, even there is no TR prefilter in the system. In other words, the energy dropping down in Fig. 6(a) is not only caused by TR prefilter. Thus, In fig. 6(a), a curve describing the energy of receiving signal has also been plotted as a reference. This is the case when there is no power control components in the transmitter, which makes it hard to give the "real" $D(d_0,d)$ of TR. When the transmitter has the capability to dynamic adjust the transmitting power so that the receiver receive identical power, despite their location. we then can remove the energy loss curve caused by free propagation. Fig. 6(b) shows the $D(d_0,d)$ curve caused by TR prefilter, assuming



(a) Transmitted Pulse (b) Impulse Response

Fig. 4. Channel impulse response of the hallway: simulation result. The impulse response is calculated by Eq. (14) for 3D case with $N=10$, $\varepsilon_r=15$, $d_0=10$. LOS has been blocked.

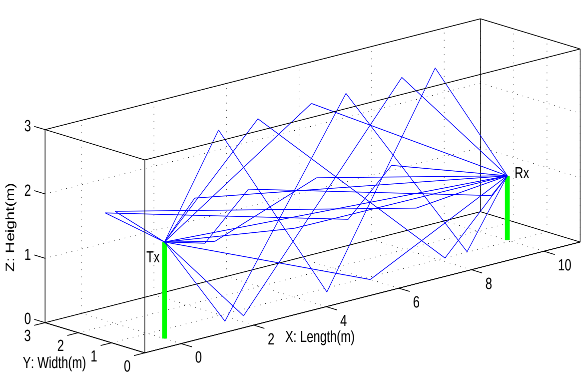
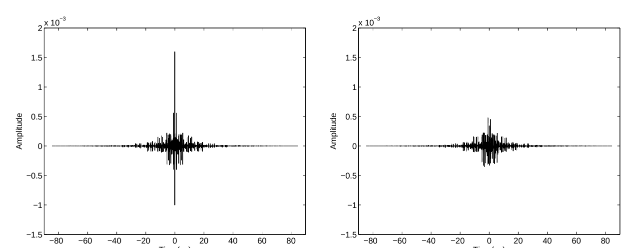
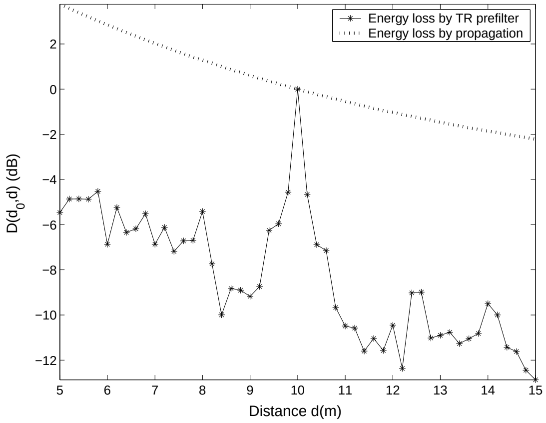


Fig. 3. An example of 3D Ray tracing result in the hallway.

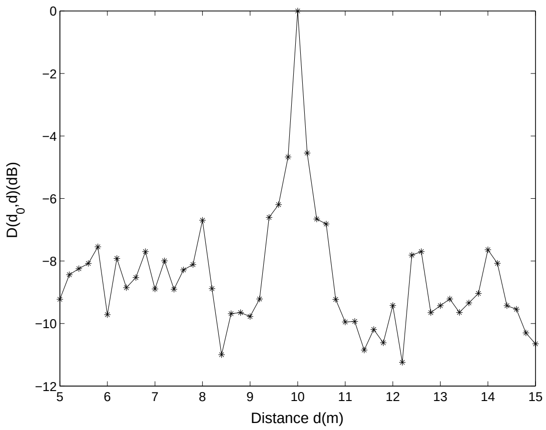


(a) $h(\vec{r}_0,t)$ (b) $h(\vec{r}_1,t)$

Fig. 5. Equivalent channel impulse response(CIR). (a) is the equivalent CIR of the intended user located at $d_0=10m$; (b) is the equivalent CIR of the unintended user with $1m$ away from the intended user.



(a) Directivity $D(d_0, d)$ without power control in the system



(b) Directivity $D(d_0, d)$ with power control in the system

Fig. 6. Spatial focusing characterized by the parameter Directivity $D(d_0, d)$. In (a) it is assumed there is no power control capability in the transmitter. The energy curve for the receiving signal has been plotted as a reference. (b) is for the case that the transmitter has the capability to adjust the power so that the receiver receiving identical power despite their location.

the receiving energy fixed when the receiver moving away from d_0. A 10-dB energy down can be observed in Fig. 6(b) when the undesired receiver is 1m away from the intended receiver.

Note that time reversal(TR) technique take advantage of the multipath. Therefore, the richer the multipath, the better the performance. For our case, one can see that the multipath is not that many. Two reasons cause the multipath is fewer than that in practical case. The first one is that we can not trace every path due to the limitation of the algorithm, e.g., the diffraction path caused by possible large edge. Another reason is that in reality, the environment is much more complicated than the model used in this paper. Therefore, the spatial focusing results provided in this paper is the worst case in reality. Some experimental results about TR spacial focusing in a hallway environment has been reported in [15] and the same trend has been observed.

V. CONCLUSIONS

The TR technique takes advantage of multiple scattering. Using a hallway as an example, the spatial focusing has been demonstrated. The impulse response of the hall way is conveniently obtained through time-domain ray tracing. Although similar work has been done in acoustics, in electromagnetics this demonstration appears be done for the first time. Our approach of using time domain ray tracing is also novel for TR in electromagnetics. The simulation model can be conveniently applied to study the impact of the building size on TR. Moreover, although it is built based on hallway environment, this propagation model has a lot of other applications. e.g., this model is well suited to be used to model UWB signal propagating in an urban canyon.

VI. ACKNOWLEDGMENTS

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