Using Audio Ray Tracing to Calculate Room Impulse Response

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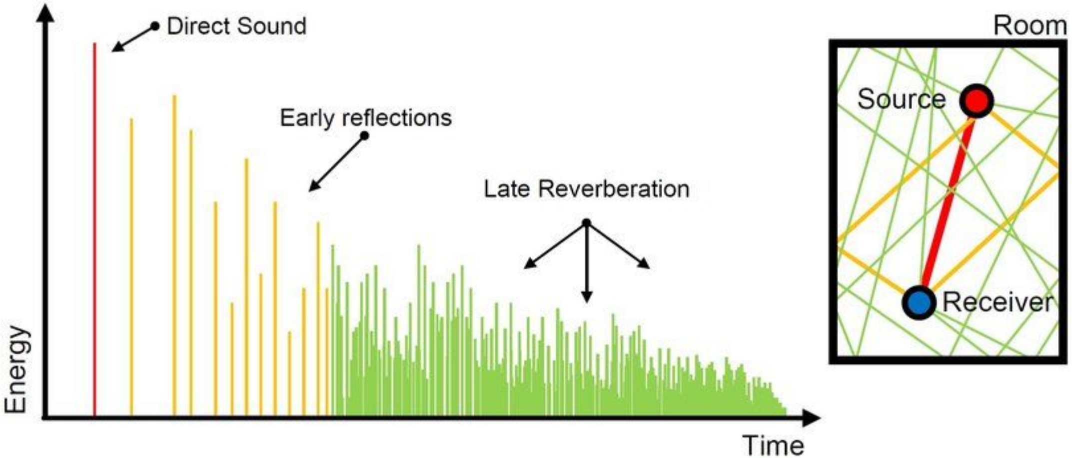
What is Ray Tracing?

- Ray tracing, regarding acoustics, is a simulation method for calculating the paths and energy of soundwaves given a source and an environment. By accurately considering the room's geometry, absorption coefficients of surfaces, diffraction, specular vs diffuse reflection, an accurate mapping of the sound waves can be determined spatially and temporally. The process is usually stochastic (Depending on the computational power, sometimes only specular reflection is considered or phenomena such as diffraction/occlusion are not modeled or simplified).
- Usually the ray tracing algorithm stops after a certain number of reflections or when soundwaves have an energy below a certain threshold.

Room Impulse Response (RIR)

- The Room Impulse Response is a response function or a transfer function between a sound source and a receiver, within a certain room. This behavior is important to know because it characterizes how audio is received and behaves within a room. For example if there are loud reflections or echos, reverberations, etc that could affect how an audience member perceives the sound at a certain location.

[1]



Given an impulse from a source, at a certain location of a receiver, the loudness (or energy) is plotted as a function of time. This characterizes the direct sound from source, reflections, and reverberations, as well as potentially a noise floor.

(RIR) Ideal Calculation & Explanation

- Assuming that your system is Linear Time Invariant, a linear combination of input signals results in a linear combination of output signals, the RIR can be defined as (2). Where s(t) is your input signal (source) and g(t) is your output signal measured by the receiver. h(t) is the room impulse response. From the RIR you can also get the frequency response by taking the Fourier transform.
- Ideally the input signal from your source is close to a Dirac Delta function.

$$s(t) = \int_{-\infty}^{\infty} s(\tau)\delta(t-\tau)\mathrm{d}\tau.$$

[2]

$$g(t) = \int_{-\infty}^{\infty} h(t)s(t-\tau)\mathrm{d}\tau = h(t) * s(t).$$

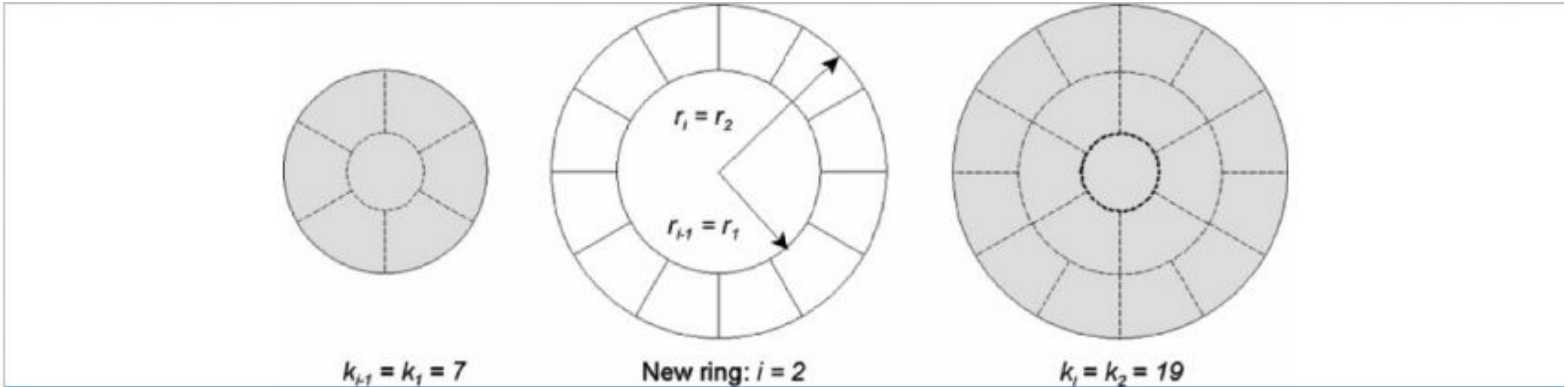
$$G(f) = \mathcal{F}\{g(t)\} = \mathcal{F}\{h(t) * s(t)\} = H(f) \cdot G(f).$$

RIR Method Equal Area Ray Tracing

- Each sound source is modeled as a sphere, and divided into an equal area of unit cells. First consider a disk, each disk is divided into N rings. Each ring has an external radius r_i and an internal radius r_{i-1} with k_i cells in each radius. Based on the condition that two consecutive circles have have cells with the same area, the following condition is imposed. (Based on IEEE paper in 2014 Audio, Language, and Image Processing Conference)

$$k^*_{i-1} S_{cell} = \pi r^2_{i-1}$$
$$k^*_{i-1} \; S_{cell} = \pi r^2_i \quad \text{then} \left(\frac{r_i}{r_{i-1}}\right)^2 = \frac{k_i}{k_{i-1}}$$

[3]



RIR Method Equal Area Ray Tracing

- Now we can extend the results into equally partitioning the surface area of a spherical cap, first depending on how many rings you want to partition the sphere into. First depending on the zenithal angle of the new ring, the radius of the ring can be determined. From their, the number of unit cells within each area projection of the ring can be determined as well as the area of each unit cell.

$$a_{i\_disk} = \frac{2\pi}{k_i - k_{i-1}} \frac{r_i + r_{i-1}}{2} \frac{1}{r_i - r_{i-1}} = \frac{\pi}{k_i - k_{i-1}} \frac{r_i^2 - r_{i-1}^2}{(r_i - r_{i-1})^2}$$

$$a_{sphere} = \frac{S_{sphere}}{(\theta_{i-1} - \theta_i)^2} = \frac{(\varphi_j - \varphi_{j-1})(\cos\theta_{i-1} - \cos\theta_i)}{(\theta_{i-1} - \theta_i)^2}$$

$$2\pi(1 - \cos\theta) = \pi r^2$$

$$\frac{a_{i\_sphere}}{a_{i\_disk}} = \frac{S_{sphere}}{(\theta_{i-1} - \theta_i)^2} \frac{(r_{i-1} - r_i)^2}{S_{disk}} = (\frac{r_{i-1} - r}{\theta_{i-1} - \theta_i})^2$$

$$a_{is\_sphere} = \pi(\frac{r_i - r_{i-1}}{\sqrt{k_i} - \sqrt{k_{i-1}}} \frac{1}{(\theta_i - \theta_{i-1})})^2$$

[4]

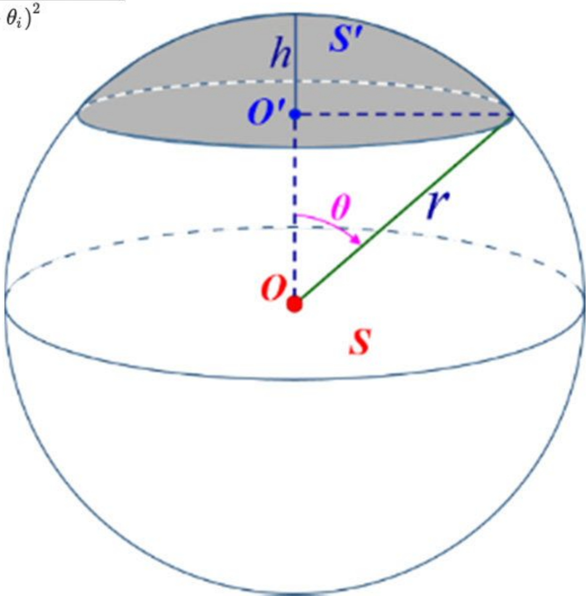
$$\theta_i = \theta_{i-1} - \frac{2}{a_{i\_sphere}} \sin\frac{\theta_{i-1}}{2} \sqrt{\frac{\pi}{k_{i-1}}}$$

[3]

$$r = 2\sin\frac{\theta}{2}$$

$$k_{i-1}^* S_{cell} = \pi r_{i-1}^2$$
$$k_{i-1}^* \ S_{cell} = \pi r_i^2$$

$$\text{then} \left(\frac{r_i}{r_{i-1}}\right)^2 = \frac{k_i}{k_{i-1}}$$



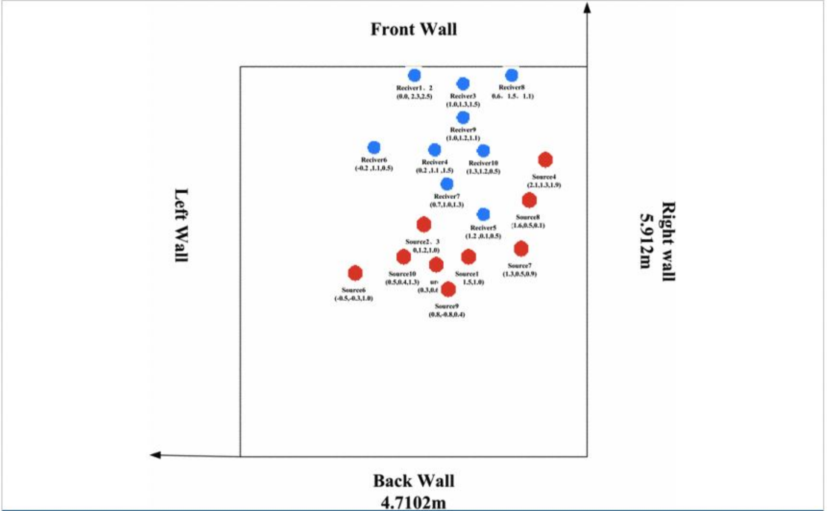
Implementation

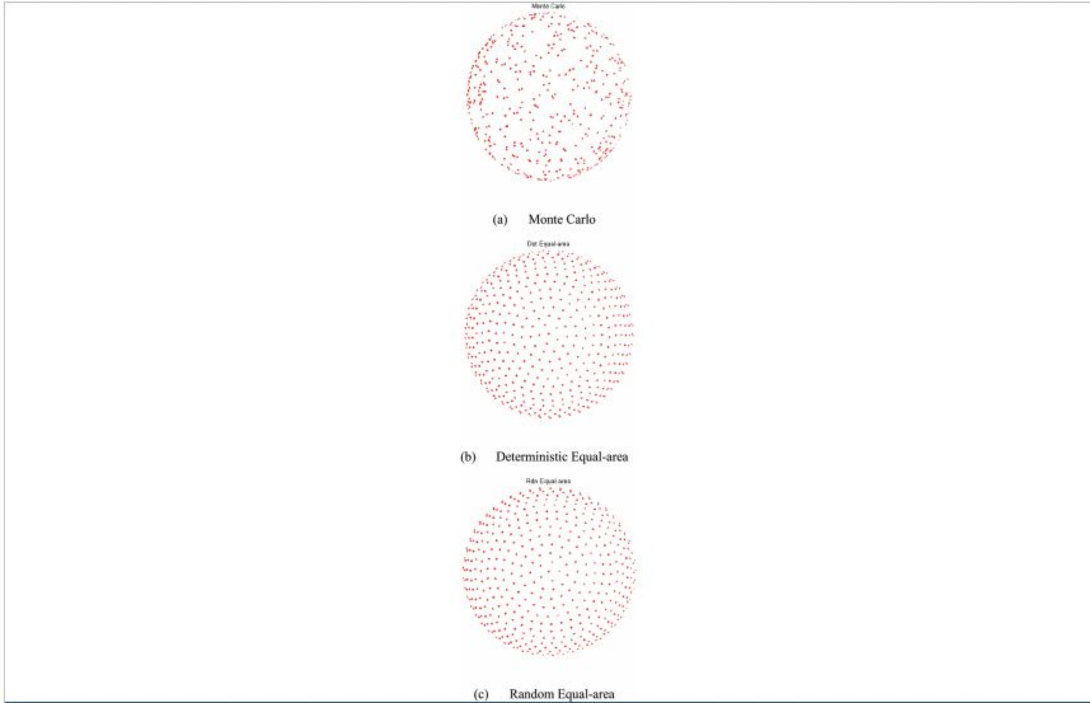
- This method was implemented in a shoebox room with dimensions 5.912 ×4.7102×5.4348 (m). The absorption coefficient for each wall was identical (0.01) and assumed to be constant over the frequency bandwidth. Attenuation by air was also considered.

[3]

Distribution of number of area patches per source from Hemisphere (0 azimuth 90 elevation angle) according to different methods.

[3]





Ray Tracing Algorithm

[5]

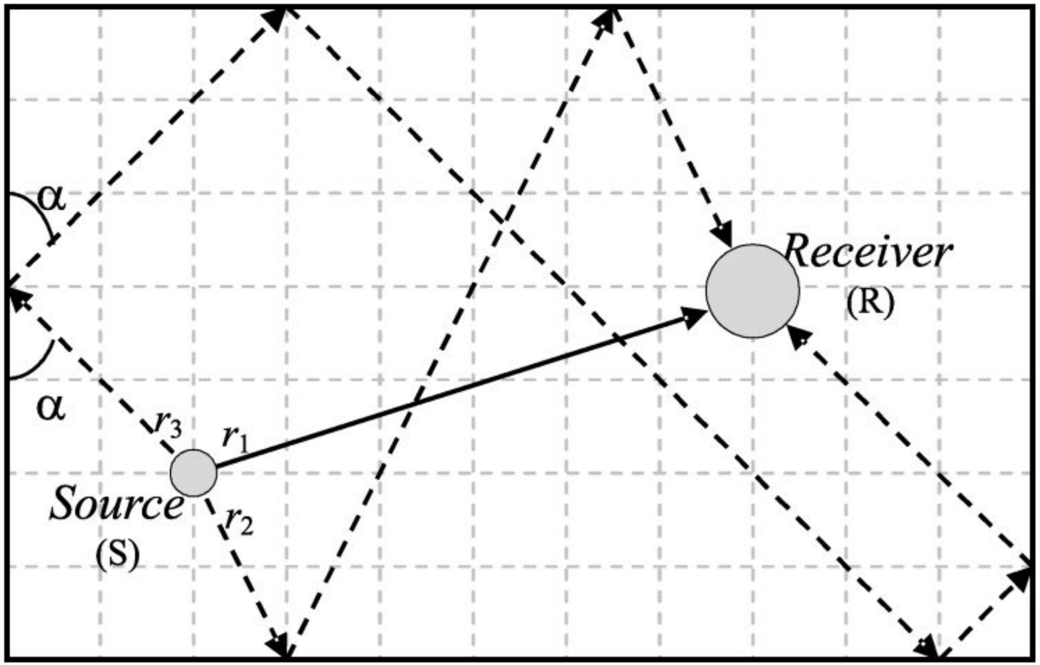


Fig. 1. Tracing three rays emitted from source point in 2D environment.

Ray Tracing Algorithm

- The following expression can be used to calculate the impulse response. j represents the jth octave band, n represents the nth sound ray from the source, i represents the ith segment of ray n's path from source to receiver, d_i is the distance of the ith segment of ray n, ψ is the total number of path segments of ray n. The reflection coefficients for the i-th segment reflected for the jth octave band is g_i^j . t_n is the instant of arrival of ray n from source S to receiver R. In the previous paper, the algorithm was cut after only 2 reflections.

$$h_n^j(t) = (-1)^{\psi-1} \left(\prod_{i=S}^{R} g_i^j \right) \cdot h_S \left(t - \sum_{i=S}^{R} \frac{d_i}{v_{\text{sound}}} \right)$$

[5]

$$= \begin{cases} 0 & \text{if } t \neq t_n, \\ (-1)^{\psi-1} \left(\prod_{i=S}^{R} g_i^j \right) \cdot \delta \left(t_n - \sum_{i=S}^{R} \frac{d_i}{v_{\text{sound}}} \right) & \text{else,} \end{cases}$$

Ray Tracing Algorithm

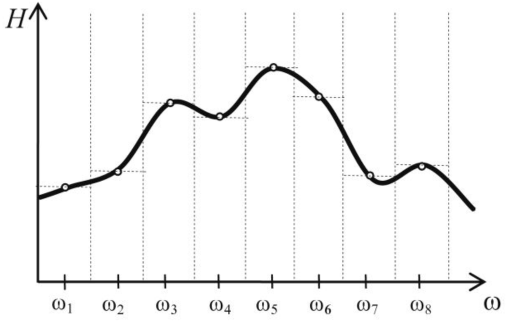
- The discrete version of the total impulse response at the receiver can be represented as $h(t) = \sum_{i=1}^{M} h_i(t).$ where $h_i(t)$ is the superposition across the octave bands.
- The RIR can also be transformed into the frequency domain as

$$H(\omega) = \mathfrak{F}\{h(t)\} = \mathfrak{F}\left\{\bigcup_{j=1}^{8} h^j(t)\right\}.$$

[5]

$$h_k = h(t_k) = \bigcup_{j=1}^{8} h_k^j.$$

Ray Tracing Algorithm



Ray n	Distance	Time Elapsed [sec]	Amplitude
r1	**6.32**	0.0186	**1**
r2	2.24+7.83+3.35 = **13.42**	0.0395	1×0.4×0.4 = **0.36**
r3	2.83+4.24+9.90+1.41+4.24=**22.63**	0.0666	1×0.6×0.4×0.6×0.4 = **0.0576**

Figure 2 shows the impulse response of a room given in Fig. 1. In this example, only tree rays are taken into consideration and are subject to simulation. In a more realistic scenario, the typical number of rays should be at least several tens of thousands.

[5]

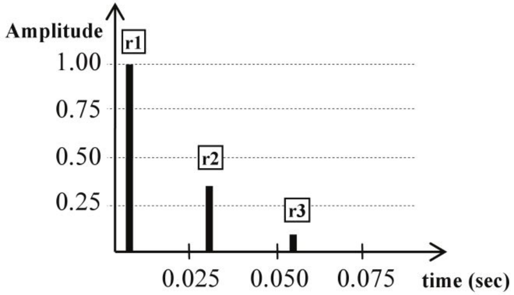


Fig. 2. Impulse response of the example room based on three rays.

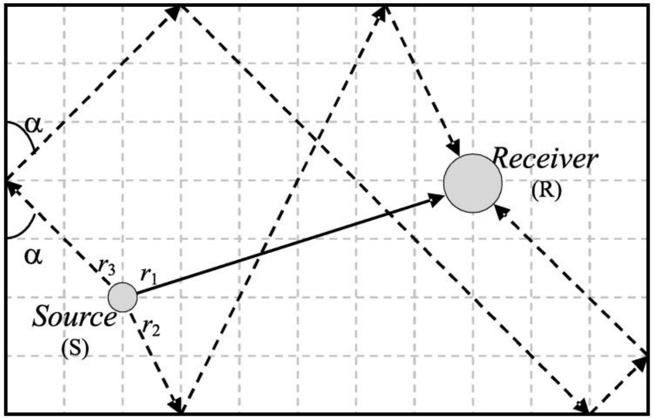
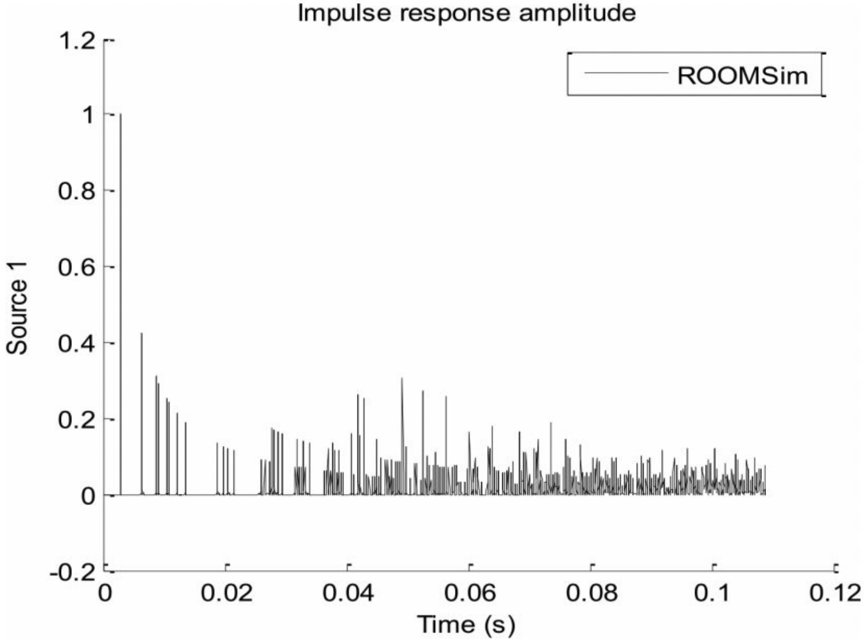


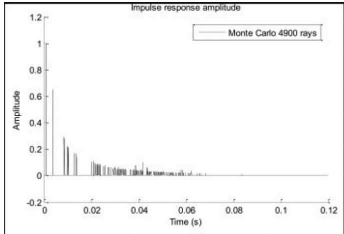
Fig. 1. Tracing three rays emitted from source point in 2D environment.

Results Compared to ROOMSIM

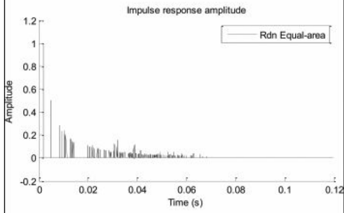
ROOMSIM is a fairly fast and accurate room acoustics modeling tool in MATLAB used for “simpler” shoebox models. The ROOMSIM results are essentially the benchmark comparison for the IEEE paper mentioned earlier.



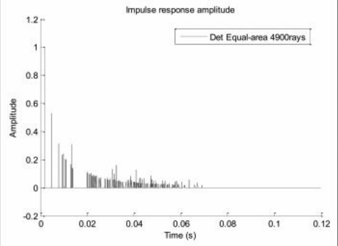
As can be seen, the Equal Area sound source method is more accurate than a Monte Carlo method (closer to ROOMSIM) with only 2 reflections.



(a) RIRs simulated by Monte-carlo



(b) RIRs simulated by Rdn Equal-area



(c) RIRs simulated by Det Equal-area

References

1. Pelzer, Sönke & Aspöck, Lukas & Schröder, Dirk & Vorlaender, Michael. (2014). Integrating Real-Time Room Acoustics Simulation into a CAD Modeling Software to Enhance the Architectural Design Process. Buildings. 4. 113-138. 10.3390/buildings4020113.
2. Klein, Johannes Christian. “Directional Room Impulse Response Measurement.” *RWTH Aachen University*, 2020.
3. Gu, Chengcun, et al. “Room Impulse Response Simulation Based on Equal-Area Ray Tracing.” *2014 International Conference on Audio, Language and Image Processing*, 2014, https://doi.org/10.1109/icalip.2014.7009911.
4. Shi, Yintao & Zhao, Gang & Wang, Maomei & Xu, Yi & Zhu, Dadong. (2021). An Algorithm for Fitting Sphere Target of Terrestrial LiDAR. Sensors. 21. 7546. 10.3390/s21227546.
5. Alpkocak, Adil, and Malik Sis. “Computing Impulse Response of Room Acoustics Using the Ray-Tracing Method in Time Domain.” *Archives of Acoustics*, vol. 35, no. 4, 2010, pp. 505–519., https://doi.org/10.2478/v10168-010-0039-8.