

# Enhanced Modeling of Head-Related Impulse Responses Towards the Development of Customizable Sound Spatialization

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*Abstract:* - Audio spatialization is a rapidly growing field in acoustics and audio signal processing. Measurements and models of head-related impulse responses (HRIRs) of human subjects or KEMAR dummy heads are the primary source of information for research on spatial audio. The information contained in HRIRs measured at various azimuth and elevation angles is sufficient for synthesizing realistic three dimensional spatial audio for headphone or loudspeaker listening. Currently, however, designers must decide between the need for specialized equipment to measure the individual HRIRs of all potential users or the low fidelity achieved with the use of HRIRs obtained from a dummy head. To overcome this problem, research is underway to develop a method to create customized HRIRs. Using signal processing tools, such as Prony's signal modeling method, an appropriate set of time delays and a resonant frequency was used to approximate the measured HRIRs, with the goal of establishing a general HRIR model that could be instantiated from anatomical measurements of the prospective listener. During more recent experimentation, the Prony method was substituted by the Steiglitz-McBride iteration method and a noticeable improvement was achieved. This paper reports on our assessment of the statistically significant improvement in the approximation when the Steiglitz-McBride iteration method is used instead of the Prony method, for HRIR decomposition.

*Key-Words:* - Head-Related Impulse Responses (HRIR), Prony modeling method, Steiglitz-McBride iterative approximation method, customizable spatial audio.

## 1 Introduction

Three dimensional (3-D) spatial audio has become increasingly popular in scientific, commercial and entertainment systems [1]. Spatial audio can be used in a variety of applications, from assistance for the visually impaired to enhancement of computer video games. Currently, there are two methods to achieve spatial audio: multi-channel or two-channel. The multi-channel approach requires that speakers be physically positioned around the listener (e.g., Dolby® 5.1 array). This is an effective but expensive solution and is impractical for a majority of applications. The two-channel approach is more practical, especially considering that it can be implemented using digital signal processing (DSP) techniques and delivered to a listener through a pair of speakers or headphones. Special filters are required in order to achieve spatial audio in a two-channel system. These linear filters are

characterized by their impulse response, known as head-related impulse responses (HRIRs). HRIRs model the effect of anatomical (torso, head, external ear, etc.) and environmental (walls, floor, etc.) factors which cause modification of a sound as it propagates from its source to each of the listener's eardrums. Therefore, every position and each ear will have a specific HRIR. Convolution of a sound signal with the two HRIRs corresponding to a specific source position results in a binaural sound (left channel, right channel) that, when played to a listener through stereo headphones will cause a perception similar to that of a sound emanating from the source location in question (Fig. 1).

Currently, there are two main types of HRIRs, according to their creation: generic or individual. Generic HRIRs are obtained from measurements made on a manikin head (e.g., M.I.T.'s measurements of a KEMAR Dummy-Head

Microphone [3]) or using a limited number of subjects to represent the general population (e.g., the CIPIC Database [4]). This type of generic HRIRs does not have as high spatialization fidelity as individual HRIRs [5], which require that the actual prospective user of the spatialized audio system undergo time-consuming measurements with specialized and expensive equipment. Unfortunately, this severely limits the access to HRIRs obtained this way. As a result of this, a majority of the HRIRs in use are generic.

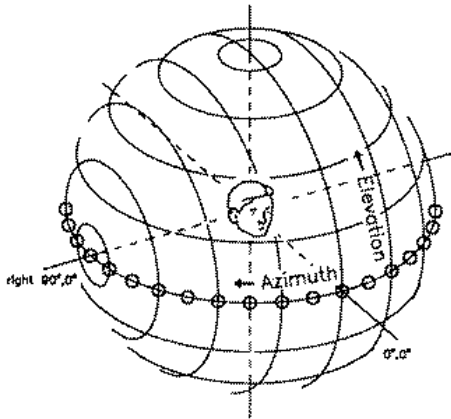


Fig. 1. Diagram of spherical coordinate system [2]

Our group is pursuing the definition of an HRIR model requiring a reduced number of parameters that could be instantiated with values derived from simple anatomical measurements from the prospective listener. This would generate customized HRIRs, as an alternative to generic or individual HRIRs. Customized HRIRs were obtained with a high percentage of fit in [5]. Our pinna model (Fig. 2) consists of a resonance block that feeds into four different magnitude and delay pairs. The outputs of these parallel paths are then re-combined to result in a customized HRIR [5][6]. Our initial goal was to verify that experimentally measured HRIRs could be decomposed to obtain parameters for our model that would result in a reasonably similar "reconstructed" HRIR. The required HRIR decomposition was originally accomplished by successive application of the Prony method of signal approximation [5]. The algorithm for Prony implemented was the method described in reference [7]. Our algorithm for successive deconstruction of an experimentally measured HRIR, such as the one shown in Figure 3, is detailed in [6]. The objective of the process is to obtain scaled and delayed damped sinusoidal components, such as those shown in Figure 4, which specify the associated parameters to instantiate the resonance, magnitudes and delays needed to approximate the original HRIR using our model. The adequacy of the "reconstructed" HRIR that results was evaluated by a measure of "fit" between the original HRIR and the one reconstructed using the model.

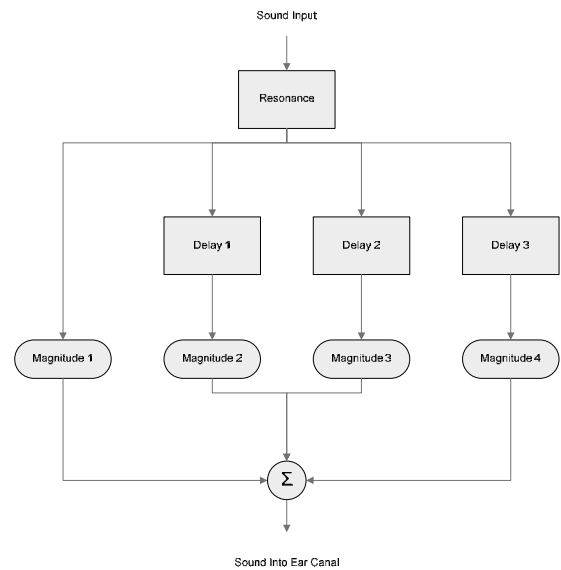


Fig. 2. Block diagram of pinna model

Recently, these experiments were repeated but the Prony method was substituted by the Steiglitz-McBride iteration method ("STMCB"). The STMCB method is similar to Prony in that it also tries to find an infinite impulse response (IIR) model for a signal. The STMCB method attempts to minimize the squared error between the impulse response and the signal it approximates in an iterative fashion. A noticeable improvement was observed after the substitution of Prony with STMCB for HRIR modeling. The algorithm implemented for the STMCB method is as described in reference [8].

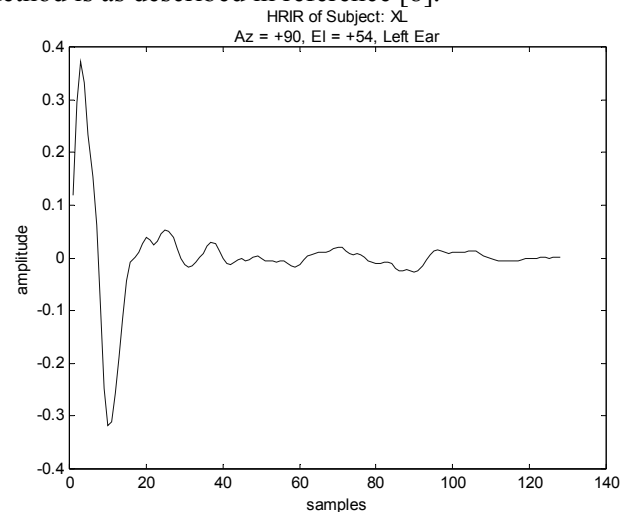


Fig. 3. The HRIR to be deconstructed

## 2 Methodology

The apparent advantage of using the STMCB method prompted a systematic evaluation of this performance difference. The following subsections describe the

methodology used to compare STMCB and Prony for HRIR modeling.

## 2.1 Iterative HRIR fitting

In this experiment, statistics will be utilized to rank the performances of the two modeling methods when used for HRIR analysis. The use of a database that is a good representation of the prospective user population is needed to obtain statistically valid results. A subset of the CIPIC HRIR database, which contains 45 subjects recorded at 44.1 kHz with various anatomical properties for multiple azimuths and elevations, was chosen for the comparison [1]. Our analysis focused on HRIRs for the right ear, for sources at ear level (0° elevation), and involved 25 azimuth values, which range from -80° to 80°.

In order to accelerate the process of comparing the two methods, a Matlab® script was created to iterate through the CIPIC database. Each HRIR signal was decomposed into three separate signals: the primary resonance and two resonances with delays which will be referred to as echoes.

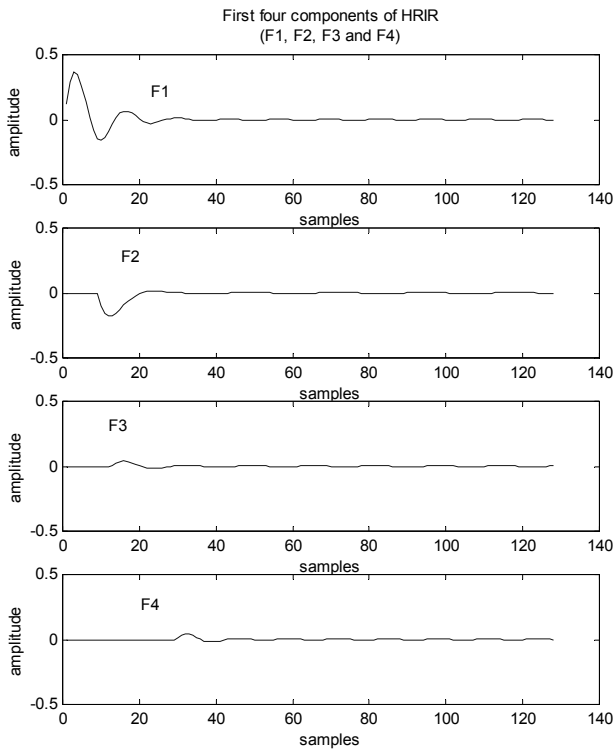


Fig. 4. The four components of the HRIR shown in Figure 3, with their respective delays [5]

This is similar to the research performed in [5] with the exception that the last (third) echo is not considered here. For example, Fig. 4 shows a decomposition of a signal using Prony in [5]. In the experiment reported in this paper

everything would be identical, except that signal F4 would not be extracted. It is apparent that the first three signals contain most of the power present in the HRIR. Hence, in an effort to increase speed of the algorithm only three signals will be extracted. The signals are obtained by passing a small “window” or segment of the original signal to one of the approximation methods (Prony or STMCB) which will return a 2<sup>nd</sup> order IIR representation that best approximates the window passed. In an additional effort to reduce computation time, the window sizes are restricted to certain ranges determined by previous work in this area [5]: the window used to determine the first echo must start at least 5 samples into the HRIR segment analyzed, which results in window1 in Fig. 5 starting at 5. Additionally, the windows are not allowed to grow wider than 10 samples. Once the three signals are extracted, an HRIR can be created from these components by adding them together at the appropriate delays, and can be compared to the original HRIR in terms of mean square (MS) value:

$$\text{Error} = \text{Original HRIR} - \text{Reconstructed HRIR}, \quad (1)$$

$$\text{Fit} = [1 - \{\text{MS}(\text{Error})/\text{MS}(\text{Original HRIR})\}]. \quad (2)$$

The percentage fit (“fit”) between the original HRIR and the reconstructed HRIR was calculated for every subject and every azimuth, and used as the figure of merit to compare the performance of STMCB and Prony for this modeling task.

## 2.2 Statistical Significance of the Improvement

Matlab® was utilized again to perform statistical analysis of the results obtained from the algorithm described in the previous section. The fit obtained when STMCB was used was subtracted from the fit obtained when Prony was used, for each azimuth of every subject. The 45 differences for one azimuth constituted a single sample and there were 25 samples (i.e., 25 azimuths) in total.

The following hypotheses were tested to determine if STMCB significantly improved the fit percentage:

$$H_0: \mu = 0. \quad (3)$$

$$H_a: \mu > 0. \quad (4)$$

Here  $\mu$  is the mean improvement that would be achieved by using STMCB instead of Prony in the modeling process. The null hypothesis says that no improvement occurs, and  $H_a$  says that the fit with STMCB is higher, on average.

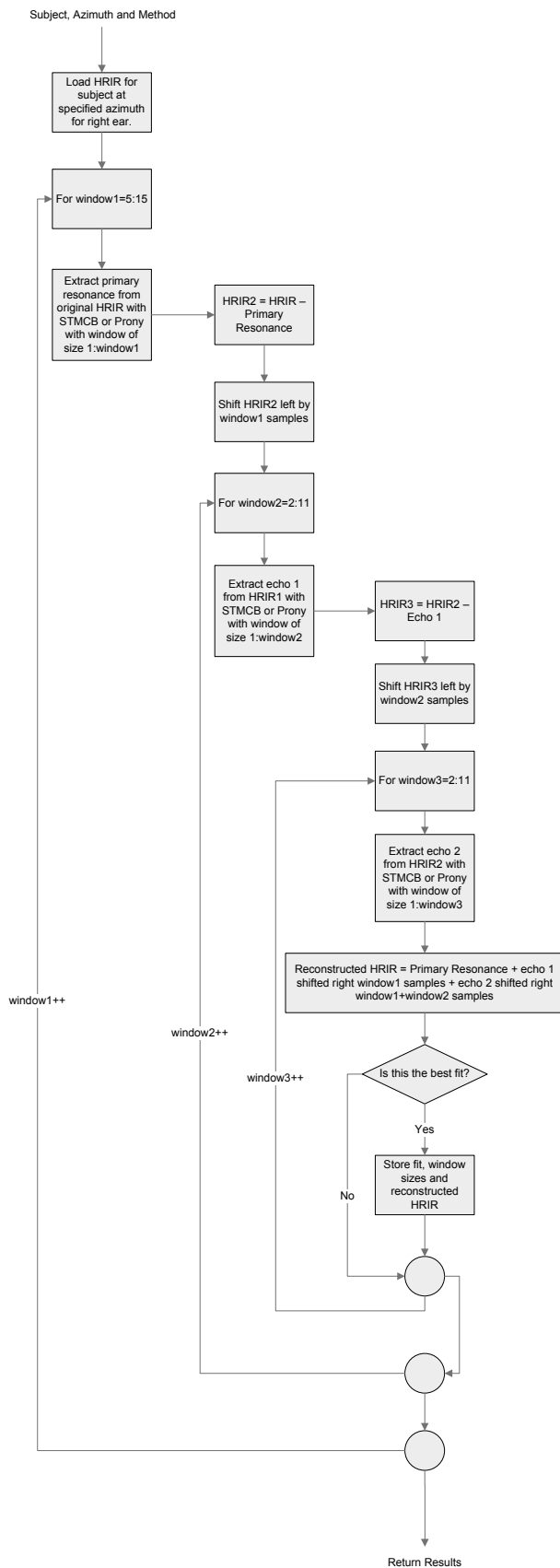


Fig. 5. Flow chart for the iterative process that determines best fit.

In this case, the one-sample  $t$  statistic is:

$$t = \frac{\bar{x} - 0}{s / \sqrt{n}}, \quad (5)$$

were  $\bar{x}$  is the sample mean,  $s$  is the standard deviation and  $n$  is the sample size.

The results of the significance test will determine if STMCB outperformed the Prony method for HRIR analysis. Unfortunately, the size of the improvement cannot be determined from these results. A statistically significant but very small improvement would not be sufficient to claim that STMCB is a superior method. A confidence interval is used to remedy this problem. The confidence interval will display how much STMCB improved over Prony with a margin of error:

$$\bar{x} \pm t * \frac{s}{\sqrt{n}}. \quad (6)$$

The procedure followed in this study is tailored after examples presented in [9].

### 3 Results and Discussion

This section summarizes and discusses the results obtained. A basic mean of the fits and the gains (fit with STMCB - fit with Prony) achieved for each azimuth was the first calculation obtained. An increase in fit and gain was achieved for every azimuth when the STMCB method was used. Unfortunately, this is not enough to establish a statistically significant difference between the performances of the methods. Hence, a t-test was utilized to compare the methods for each azimuth.

The t-test algorithm used was a predefined script in Matlab® called “ttest.” This command performs the statistical analysis algorithm described in section 2.2 of this paper. The command provides the values of the t-statistic, as well as the associated p-value, i.e., the probability that the value of the t-statistic is equal to or more extreme than the observed value by chance, under the null hypothesis (mean difference = 0). Additionally, the command provides both limits of a 95% confidence interval on the mean [10]. If the null hypothesis cannot be rejected, then the difference is not significant ( $p > 0.05$ ). Otherwise, the null hypothesis is rejected, with  $p < 0.05$ , i.e., for these azimuths the use of STMCB resulted in a significant improvement over the use of Prony. With the exception of three azimuths ( $10^\circ$ ,  $15^\circ$  and  $20^\circ$ ) the null hypothesis could be rejected. This means that, for a majority of the angles studied, a significant increase in fit was observed when STMCB was used instead of Prony.

Beyond the global analysis of the modeling results to conclude that the improvement achieved by using STMCB instead of Prony was statistically significant, some specific cases were analyzed in further detail to help in the interpretation of their results. For example, HRIRs that displayed extremely high or low fits were examined manually, as displayed in figures 6 and 7. In these figures, the top plot displays the individual HRIR, the middle plot displays the HRIR reconstructed using STMCB and the bottom displays the HRIR reconstructed using Prony. Figure 6 (subject 24, 35° azimuth) displays reconstructed HRIRs that had a high percentage fit of about 94%. This is consistent because the main morphology is maintained when the HRIR is reconstructed using either Prony or STMCB. These results, in turn, confirm that the limitation to the modeling of just two “echoes” was not too restrictive. Conversely, figure 7 (subject 27, 20° azimuth) shows a plot with relatively low percentage fit of about 28%. As can be seen in this figure, the reconstructed HRIRs do not resemble the original HRIR. It would seem that both methods were able to approximate the second positive “peak” in the HRIR, appearing at a latency of about 12 sampling intervals. On the other hand, it is apparent that both STMCB and Prony minimized the error in the approximation of the first positive peak and the negative peak that immediately follows it by substituting both with a data segment that hovers around zero, which is clearly inappropriate. It is possible that the separation of these two echoes in HRIRs such as these might be very small, particularly considering the limited temporal resolution afforded by the 44.1 kHz sampling rate employed in the development of the CIPIC Database, as compared to the 96 kHz sampling rate used in other previous studies that have attempted this kind of HRIR decomposition [5][6]. However, further research is needed to ultimately pinpoint the reasons for the degradation of this technique for some azimuth values.

## 4 Conclusion

There is an interest in the development of methods of audio spatialization that can be easily “customized” to provide each individual listener with maximal imaging fidelity. Our group has pursued this goal through the establishment of a dynamical model capable of generating head-related impulse responses (HRIRs) that can be used for audio spatialization. An emphasis has been placed in reducing the number of parameters required to instantiate this model, and on the fact that these parameters should be, in the long run, easy to define from simple anatomic measurements obtained from each prospective user of the spatial sound system.

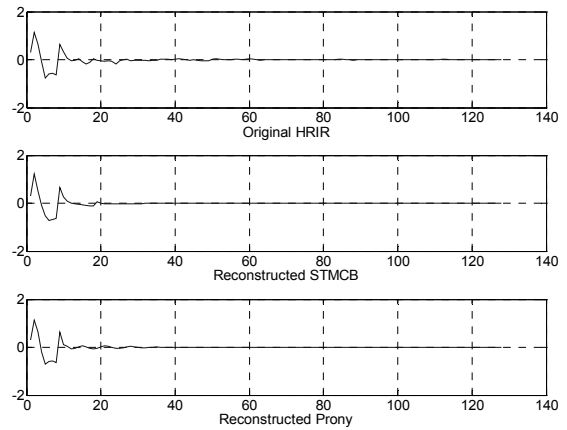


Fig. 6. Plot of the original and reconstructed HRIRs for subject 24 at 35° azimuth.

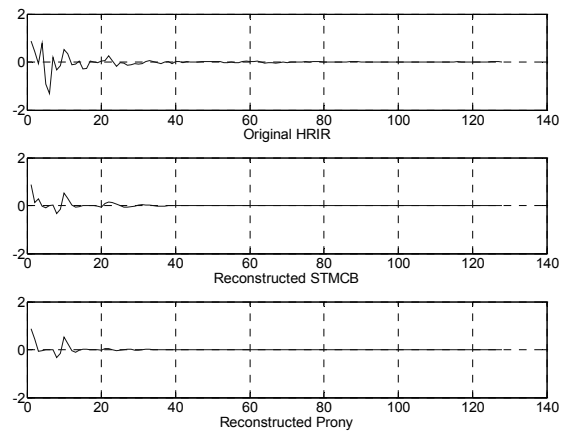


Fig. 7. Plot of the original and reconstructed HRIRs for subject 27 at 20° azimuth.

With this aim, one of our initial goals was to show that specific sets of parameter values (e.g., resonance characteristics, echo delays and magnitudes) can be found that will result in modeled HRIRs that are a good approximation of measured individual HRIRs. Since we have proposed a method to find the necessary model parameters from a measured individual HRIR, by deconstructing it into multiple second order responses (that appear resized and delayed), it is of interest to identify the modeling approach that achieves the highest efficiency in this process. In this study, the Steiglitz-McBride (STMCB) signal approximation model has been compared to the Prony approximation method, in its use as the core of the iterative process used to deconstruct HRIR sequences. This systematic study showed that, for the HRIRs from the CIPIC database with 0° elevation and azimuths ranging from -80° to 80°, the STMCB method outperformed the Prony method for the vast majority of

azimuth values, as judged by the enhanced “fit” (in the least squares sense) between the HRIR created by reconstruction from the three 2<sup>nd</sup> order partial responses found, to the original, experimentally measured HRIR. There were only three azimuth values (10°, 15° and 20°), out of 25, for which the improved performance of the STMCB approximation did not prove to be statistically significant. It is important to note, however, that for all azimuth values (including 10°, 15° and 20°) the mean value of fit between the reconstructed HRIR and the original HRIR was higher when STMCB was used than when Prony was utilized. Accordingly, it seems reasonable to recommend the use of STMCB signal approximation methods for HRIR modeling, in general.

## 5 Acknowledgement

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