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# Phase-aberration Delay Estimation in Synthetic Transmit Aperture Diagnostic Ultrasound

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***Abstract*—Phase aberration is one of the main contributors to image degradation in ultrasound imaging . Image reconstruction is usually performed under the assumption of a homogeneous medium. However, in the presence of the spatial sound-speed inhomogeneities, this hypothesis is no longer valid and leads to error in estimating echo arrival time. Normalized Cross Correlation (NCC) is one of the most extensively studied techniques to estimate the arrival delay error and the aberration profile. However, NCC can only estimate the relative delay errors between the probe elements and can not give the mean delay error. In this paper, an algorithm was proposed to maximize the brightness and variance over a region of interest of the reconstructed image to find the mean delay error. Firstly, conventional NCC was modified to design an iterative method that estimated the relative aberration profile in the raw synthetic transmit aperture RF signals in both transmit and receive. The phase-aberration error was corrected to yield a better focused image. Secondly, an optimization-based algorithm was developed to estimate the mean value of delay error. An absolute delay error estimator is essential for the mapping of sound-speed within the medium.**

***Index Terms*—Phase Aberration, Absolute Delay, Optimization**

## I. INTRODUCTION

One of the major shortcomings in ultrasound imaging is the image degradation due to phase-aberration that compromises the beam-focusing quality. Deviation from a correct delay estimation will lead to image degradation. With regards to phase aberration, delay calculations solely based on the geometric analysis are incorrect. Many approaches have been developed for phase aberration delay correction, including: (1) maximization of speckle brightness [1], (2) minimization of the sum of absolute differences between signals at adjacent elements [2] and lastly, (3) normalized cross-correlation (NCC) method. NCC is the most widely studied delay estimation algorithm in ultrasound imaging. O'Donnell and Flax have demonstrated that normalized and non-normalized NCC techniques can be used to obtain accurate estimates of delay compensation in B-mode imaging [3] [4] . Generally, a segment of radiofrequency (RF) data in a reference received signal is compared with a segment of RF data in a delayed received signal. At each window, a pattern-matching function is utilized to find the delay where the two windows resemble each other most [5]. Regarding commonly used algorithms, normalized and non-normalized NCC give reasonable results in terms of precision and computational time [6] . The location of the peak in the NCC function represents the estimated delay.

In more recent studies NCC were used to estimate or map the speed of sound. They can be categorized into: a) global sound-speed estimators where the average speed was measured between the surface and the depth of focus. b) local velocity estimators. Anderson and Trahey method is a dynamic error delay correction algorithm that derives the average sound speed by analyzing the pule-echo data at receive channels upon a single transmission [7] . Yoon et al. measured the average sound speed by evaluating the phase variance of radio-frequency channel data in the region of interest [8] .

Here, we propose a method to estimate the mean delay error to map the sound-speed. Cross-correlation model is successful in the estimation of the relative aberration error. However, NCC is not capable of measuring the average of the error. To do so, an optimization-based algorithm was developed that maximizes the brightness and variance of an ROI when the true average delay is applied.

## II. MATERIAL & METHOD

### *A. Relative Delay Error*

Ideally, upon compensation by the geometrical delay, signals from a speckle area should exhibit a high level of similarity between neighboring elements. Phase-aberration undermines the alignment between adjacent element signals. To estimate the delay error an iterative NCC method was used. Normalized-Cross-correlation is a window matching function using the similarity of two signals .

$$NCC(\tau) = \frac{\sum_{n=n_1}^{n_2} s_{x_i}(t)s_{x_j}(t+\tau)}{\sqrt{\sum_{n=n_1}^{n_2} s_{x_i}^2(t)\sum_{n=n_1}^{n_2} s_{x_j}^2(t+\tau)}} \tag{1}$$

Here $n_2$ & $n_1$ represent the starting and ending point of the window in the signals $s_i$ & $s_j$ over which cross correlation was measured. Additionally, $\tau$ is the time shift between the two signals. The peak of the cross-correlation function is at the delay error between the corresponding receive elements $\hat{d}_{x_1,x_2}$:

$$\hat{d}_{x_1,x_2} = \arg\max_{\tau}(NCC(\tau)) \tag{2}$$

In this implementation, signals were up-sampled to 80 MHz and sub-sampling accuracy in NCC algorithm was achieved with cosine curve fitting. NCC was performed between a pair of receive elements with lag 1 (adjacent elements) & lag 2.

$$\hat{d}_{x_1,x_2} = t_{x_2} - t_{x_1} \tag{3}$$

The hat symbol is used to show the estimated value. $\hat{d}_{x_1,x_2}$ is the estimated delay error between a pair of receive elements. $t_{x_1}$ and $t_{x_1}$ are the true delay errors. Eq. 3 can be written into a matrix form as below:

$$\underbrace{\begin{bmatrix} 1 & -1 & 0 & 0 & \cdots & 0 \\ 0 & 1 & -1 & 0 & \cdots & 0 \\ 0 & 0 & 1 & -1 & \cdots & 0 \\ \vdots & & & & \vdots & \\ 0 & 0 & \cdots & 0 & 1 & -1 \end{bmatrix}}_{M} \underbrace{\begin{bmatrix} t_1 \\ t_2 \\ t_3 \\ \vdots \\ t_{N-1} \end{bmatrix}}_{t} = \underbrace{\begin{bmatrix} d_{1,2} \\ d_{2,3} \\ d_{3,4} \\ \vdots \\ d_{N-1,N} \end{bmatrix}}_{d} \tag{4}$$

The true arrival time error was estimated by taking the pseudo-inverse of the above equation:

$$\hat{t} = \left(M^T M\right)^{-1} M^T d \tag{5}$$

The estimation can be improved if M integrates both lag 1 and lag 2. That can be achieved when the corresponding matrices of $M$ and $d$ for both lags are stacked. In summary, Eq. 1 was first used to yield the delay error between a pair of receive elements $d_{i,i+p}$ with the desired lag $p$. Then the delay error for each receive element can be computed by solving Eq. 5. After that, the estimated delay was applied to the RF data to approximately correct the phase aberration. Lastly, the above process was iterated several times for further improvement.

### B. Absolute Delay Error

Since NCC cannot estimate the absolute delay value or the mean delay across the probe, an optimization- based algorithm was adapted and investigated to estimate the mean delay value. In the presence of average delay error, the focusing quality is compromised and the image intensity is weaker. Therefore we propose to maximize the speckle brightness and variance for a small region of image to estimate the mean delay error. A region of interest was selected so that it contains 5 to 6 speckles. Synthetic transmit aperture RF signal $S_{ij}(t)$ was aberrated with a known delay profile for both the transmit and receive processes, where $i$ &$j$ represent the transmit and receive elements. The $I_{xy}$, the image of the ROI was reconstructed using Eq. 6, where $t_{tr}$ is the geometrical travel time. Image was quantified by various metrics. The estimated mean value is at the maximum of the metrics when the true average delay is applied. Metrics investigated in this paper are 1) variance of the magnitude (Eq. 7), the summation of 2) magnitude and 3) square of the magnitude over the region of interest.

$$I_{xy} = \sum_{i=1}^{128} \sum_{j=1}^{128} S_{ij}(t_{tr} - 2d_0) \tag{6}$$

$$\hat{d}_0 = \arg\max_{d_0}(metrics(|I_{xy}(d_0)|)) \tag{7}$$

Notice that the depth position of the center of ROI, $y(d)$ depends on $d : y(d_0) = y(0) + d_0 * c$, where $c$ is the speed of sound. We call this adjustment of ROI as speckle tracking. Our findings showed the importance of speckle tracking. Delaying the RF by the mean delay $2d_0$ would shift the ROI by a very small value, $d_0 * c$. The estimation of mean delay error was improved by tracking the speckle area and compensating for this shift value.

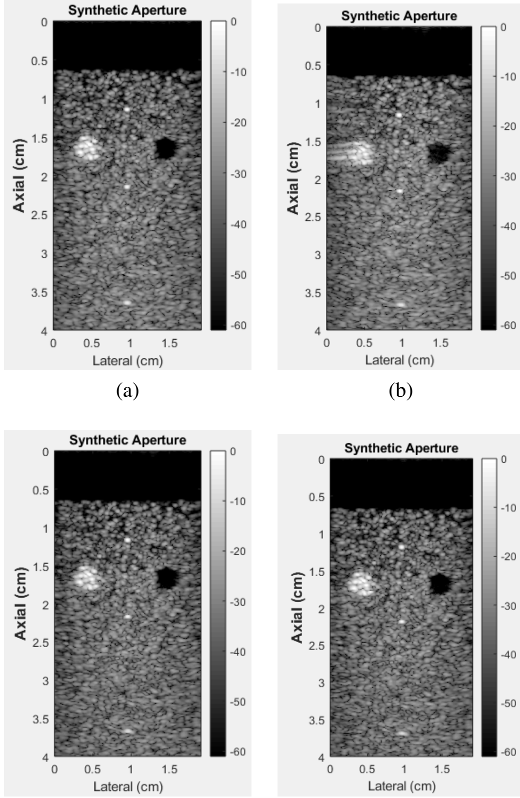
## III. Results:

Filed II ultrasound simulation [9] software was utilized to generate synthetic aperture RF signals. A homogeneous medium with known acoustic properties was simulated as illustrated in Figure 1a; where the speed of sound was 1540 $m/s$, attenuation was 0.5 $dB/MHz/cm$, and the density was 1000 $kg/m^3$. Transmission and receive events were simulated with a 128-element transducer with a pitch of 0.15 $mm$ . The simulation and image reconstruction was performed in Matlab (The MathWorks Inc., Natick, Ma). Initially RF was aberrated with a statistical delay (truth delay) over both transmit and receive to simulate phase-aberration in synthetic aperture data. The degraded image is shown in (Figure 1b).

To estimate the aberration delay, NCC algorithm defined by Eq. 1 to 5 was used. The NCC algorithm successfully calculated the relative delays . **In this implementation, cross-correlated signal lines was focused on areas with speckles.** A comparison between Figures 1b and 1c confirms the success of the algorithm while upon correction, the aberrated image was restored almost to the original accuracy. Correction with relative delay has improved the CNR and SNR.

Next, to test the accuracy of estimating the average delay error, the synthetic transmit aperture RF signal $S_{ij}(t)$ was delayed with a constant value $d$ for all the elements in both the transmit and receive process. Therefore, the total delay for $S_{ij}(t)$ was $2d$. In simulation the true average was set as -1.25 $cycles$. We maximized the brightness and variance of $I_{xy}$ (reconstructed image within the ROI) in Eq. 6 to find the corresponding mean value $d_0$. The three metrics were calculated for various trial mean delays and plotted in Figure 2. In this implementation, the ROI is centered at 0.9 $cm$ depth . In the presence of speckle tracking, for each trial of the mean value, ROI was moved vertically with the corresponding shift. As shown in Figure 2a, when speckle tracking was applied, both variance and summations exhibit a clear peak at -1.24 $cycles$, which is in the vicinity of the expected true delay (-1.25 $cycles$). When the speckle tracking was not considered, the graph has a fluctuating pattern between -2.25 $cycles$ to 2.25 $cycles$, as illustrated in Figure 2b.

our method was further investigated for various true mean delay values with speckle tracking. Algorithm was tested with



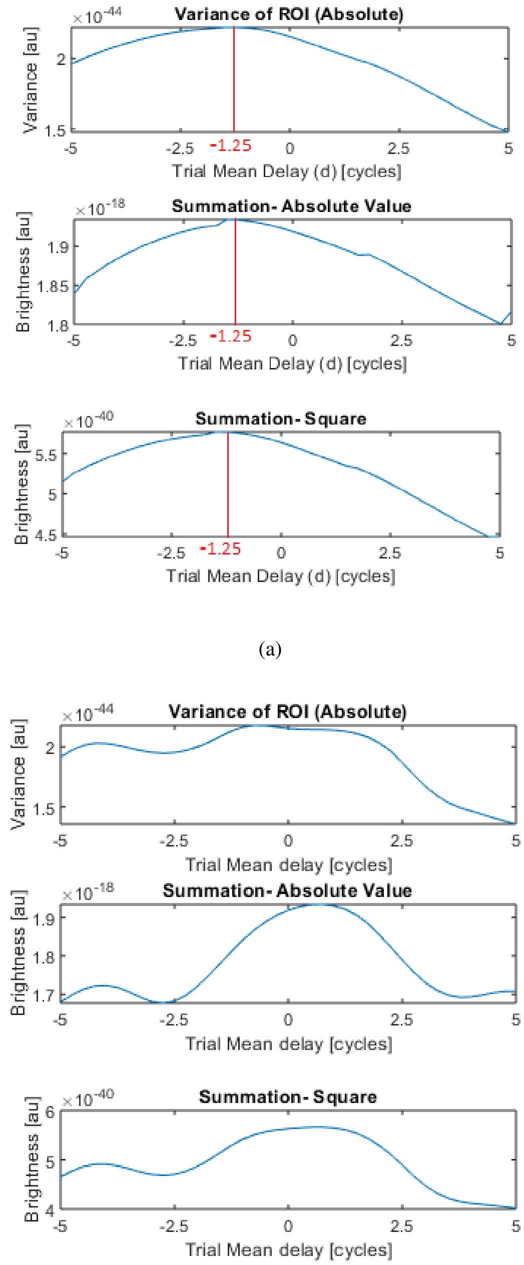

(a) (b) (c) (d)

Fig. 1: Field II simulation phantom. (a) Original reconstructed image (b) Aberrated with statistical error (c) Corrected with relative delay. Cross-correlation focus point was located on a speckle area centred at 0.5 $cm$ lateral and 1 $cm$ axial position (d) Corrected with absolute delay

RF true delays ranged between -2.5 $cycles$ and 2.5 $cycles$. The results are shown in Table I. However, when the proposed method was applied to a larger depth, the estimated average delay had a larger bias and noise. We will investigate this issue in our future work.

TABLE I: A comparison between true mean delay and estimated value when speckle tracking was considered

| **Mean Delay [cycles]** | |
|---|---|
| ***True*** | ***Estimated*** |
| -1.25 | -1.24 |
| 1.25 | 1.2 |
| -2.5 | -2.5 |
| 2.5 | 2.5 |




(a)

(b)

Fig. 2: Variance and summations of absolute values and square of absolute value (a) with speckle tracking (b) without speckle tracking versus mean delay . In this scenario the true mean delay is -1.25 $cycles$

## IV. Conclusion:

An absolute delay estimator was introduced as an improvement to cross-correlation based relative delay estimator. CC algorithm is not capable to measure the true mean delay across the aperture. The CC algorithm with cosine fitting for sub-sampling accuracy was applied to correct for the relative phase aberration. An Optimization-based algorithm was proposed to estimate the average delay error. The mean delay is at the peak of the variance and sum of the pixel intensity in ROI when the true mean delay is approached. Optimization-based algorithm was demonstrated to be sufficient for ROI centered at 0.9 $cm$ depth (Table I). More study is needed to improve the performance of the proposed method at larger imaging depth.

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