The “N-shot” maximum brightness algorithm: An efficient and robust delay-aberration estimator

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***Abstract*— The iterative “maximum brightness” delay aberration correction algorithm searches on each array element for the beamformer delay that maximizes the spatial-average speckle brightness. The array elements are optimized in turn until the entire aperture is corrected. A minimum of two transmits per line in the ROI (two “shots”) are required for each element but the actual number is typically much greater, especially when small delay steps are employed. Furthermore, thermal or motion-induced noise can introduce false, transient maxima. These often cause the iterative search to halt prematurely at incorrect delay values, a problem which is also exacerbated as the step size is reduced. This paper describes a new family of algorithms, termed “N-shot”, in which the number of shots is constant and small (as low as *N* = 2). All are based on the empirical observation that the average speckle brightness exhibits a nearly sinusoidal variation with respect to any one element’s beamformer delay. Application of *a priori* knowledge allows the phase of the sinusoid, and hence the delay aberration value for a given element, to be determined with only two shots. An additional shot allows brightness trends due to “motion noise” to be estimated and removed. Appropriate separation of the delays used for the shots reduces susceptibility to thermal noise. Compared to the iterative algorithm, this new approach is at least as fast and typically much faster, the number of transmits is deterministic and independent of delay quantization, and it has reduced susceptibility to thermal and motion noise. The effectiveness of the algorithm was tested experimentally using an artificial aberrator attached to a phased array. Comparisons between aberrated and corrected phantom images confirm the ability of the N-shot algorithm to determine delay aberrations with only two ROI firings for each array element.**

***Index Terms*— Ultrasound, aberration, maximum brightness.**

I. Introduction

The maximum brightness algorithm (MBA) is amongst the earliest proposed methods for delay aberration correction in medical ultrasound imaging [1], [2]. Like correlation-based methods [3]–[5], MBA assumes that the aberrations are usefully approximated by a near-field phase screen. MBA then derives the set of beamformer delays that maximizes the spatial average speckle brightness within a region of interest (ROI). For the case of (coherent) medical imaging, the argument [2] that this set of delays accurately records the actual delay aberrations is not as mathematically rigorous as the argument for the (incoherent) astronomical imaging case [6]. However, encouraging experimental results have been reported [7].

MBA has several advantages over correlation-based estimators: Access to per-channel RF data is not required, computational requirements are minimal, and transmit aberrations can be solved for explicitly (and independently from receive aberrations). The latter advantage may be important for harmonic imaging if the aberrations exhibit frequency dependence.

Despite these advantages MBA has not been as widely embraced by the research community as the correlation-based approaches. Perhaps the main reason is that MBA is intrinsically slow. In general, it must operate on each element of the array in turn (although speed-ups can be achieved by operating on sub-apertures [7] or on receive only [8]). This disadvantage is compounded by the fact that previously published implementations of MBA are iterative [2], [7]–[9]. A quite possibly lengthy iterative search is required on each element. Specifically, for each element in turn, after an initial ROI brightness measurement, the brightness is repeatedly re-measured as the transmit and/or receive delays are incremented or decremented by $\Delta\tau$ until a maximum is found (by observing a decline in brightness on the final measurement). Each iteration (brightness measurement) requires one transmit per ROI line. Call this collection of transmits a *shot*. In the best case, if the initial delay is within one delay quanta of the optimum for that element, then three shots are required (or two in the case of the “look-back” algorithm [9] where the current element uses the result from the previous element). However, in general, many more shots are required. The exact number depends on (a) how close the initial delay is to the optimum and (b) the delay resolution desired (i.e. the value of $\Delta\tau$). Therefore, in practice, the time required to correct the entire aperture is large and subject to uncertainty.

An additional issue with iterative MBA is that successive brightness measurements are contaminated by thermal and “motion noise.” Motion noise is the drift in average ROI brightness due to tissue or transducer motion changing the target population contained within the ROI. Either type of noise can cause iterative MBA to prematurely halt on a false peak, especially when $\Delta\tau$ is small and/or the brightness peak is relatively flat (which turns out to be the case in practice as described in the next section).

This paper describes an alternative to iterative MBA, namely *N-shot* MBA, which addresses both the speed and noise-sensitivity disadvantages of iterative MBA.

II. N-shot Maximum-Brightness Algorithms

N-shot MBA takes advantage of the empirical observation that the average speckle brightness exhibits a nearly sinusoidal dependence on beamformer delay. The problem of finding

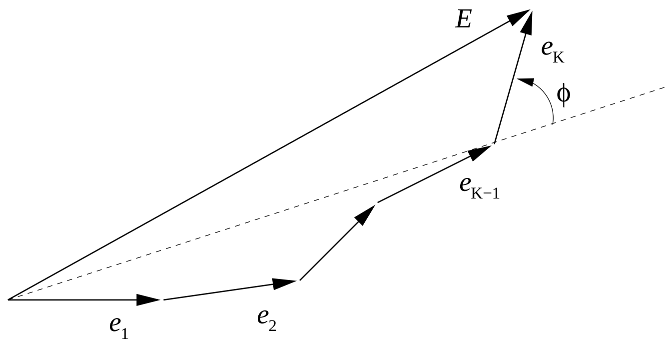

Fig. 1. Phasor diagram of the response of a K-element aperture focused onto a single target. The aperture might be aberrated as illustrated by the first $K-1$ phasors being imperfectly aligned. Phasor sum E exhibits a sinusoidal variation with respect to the phase shift ϕ applied to the final element K.

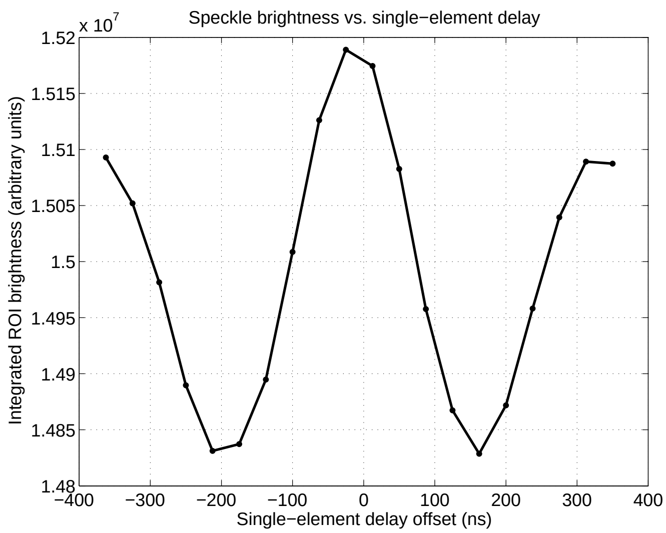

Fig. 2. Brightness fluctuations recorded from a speckle ROI within a phantom are almost sinusoidal with respect to the beamformer delay applied to a single element. f_o is approximately 2.7 MHz in this example.

the delay which maximizes brightness is then reduced to the problem of determining the parameters of a sinusoid.

The reason for the sinusoidal dependence is readily understood if we consider focusing a K-element array onto a single point target in CW, as illustrated in Figure 1. The squared magnitude of the phasor sum E, i.e.

$$|E|^2 = \left|\sum_{k=1}^{K-1} e_k\right|^2 + |e_K|^2 + 2\left|\sum_{k=1}^{K-1} e_k\right| |e_K| \cos\phi \qquad (1)$$

has an exactly sinusoidal dependence on the phase shift ϕ applied to the K^{th} (or any other) element. For practical values of K, the variation of $|E|$ is also well approximated by a sinusoid. It then follows, based on the random walk arguments presented in [2], that the average speckle brightness also has sinusoidal dependence. Furthermore, the form of (1) suggests that MBA is functionally similar to the "correlation against the beam-sum" method [5].

Figure 2 plots an experimentally measured brightness curve. Variations from a perfect sinusoid are largely explained by the large bandwidth of the pulses used. The following sections describe different nuances in the methods that can be used to determine the locations of the maxima using the N-shot approach.

A. 3-shot

The 3-shot algorithm calculates an optimal delay for a particular element from three observations of the ROI brightness as the beamformer delay for that element is set to three different values. Assume that the brightness variation B is sinusoidal with respect to the incremental beamformer delay τ, i.e.

$$B(\tau) = u + A\cos(2\pi f_o \tau - \phi) \qquad (2)$$

where u is the "DC offset," A and ϕ are the amplitude and phase of the sinusoid, and f_o is the center frequency of the ultrasonic pulse. f_o can be determined *a priori* either from knowledge of the system parameters (transmit frequency, attenuation coefficient, ROI depth) or through a single, initial calibration (e.g.: spectral analysis of measurements such as those shown in Fig. 2). Application of the angle addition rule results in the linear system

$$\begin{bmatrix} B_1(\tau_1) \\ B_2(\tau_2) \\ B_3(\tau_3) \end{bmatrix} = \begin{bmatrix} 1 & \cos(2\pi f_o \tau_1) & \sin(2\pi f_o \tau_1) \\ 1 & \cos(2\pi f_o \tau_2) & \sin(2\pi f_o \tau_2) \\ 1 & \cos(2\pi f_o \tau_3) & \sin(2\pi f_o \tau_3) \end{bmatrix} \begin{bmatrix} u \\ A\cos\phi \\ A\sin\phi \end{bmatrix} \qquad (3)$$

which can be solved for the three unknowns u, A, and ϕ. The optimal delay is $\phi/2\pi f_o$ and the corresponding optimal brightness is $u + A$.

Values of τ separated by one-quarter cycle, i.e. $\tau = -1/4f_o$, 0, and $1/4f_o$ work well, although other choices will also work.

B. 2-shot

If the delay on each element is optimized while holding the delays on all other elements at their initial values, then u remains constant over the course of the adaptation. Therefore, one of the unknowns in (3) can be eliminated and the optimum delay for each element can be determined with just two brightness measurements.

In practice, faster convergence (in the sense of fewer passes across the array) is achieved using "speckle look-back" [9]. Once determined, the delay for element k is held at its optimum value. In this case u increases as the adaptation proceeds. However, (2) can be used to predict what one of the brightness values for element $k+1$ (specifically for $\tau = 0$) would be, without actually making the measurement. Again, only two brightness measurements are required. Equation (3) is solved with two actual measurements and one virtual measurement. The look-back version of the 2-shot procedure is illustrated in Fig. 3.

C. Motion compensation

N-shot MBA can also estimate and compensate for motion-induced brightness changes. In the simplest case, motion is assumed to add a linear brightness drift:

$$B(\tau; t) = u + vt + A\cos(2\pi f_o \tau - \phi) \qquad (4)$$

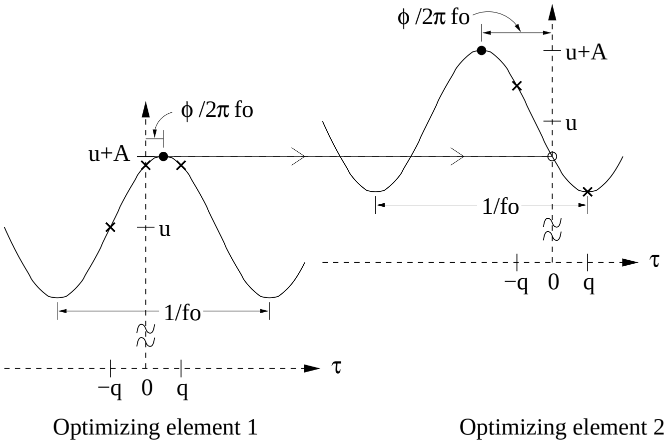

Fig. 3. The 2-shot algorithm uses the peak brightness measured for element 1 as the virtual, zero-delay, measurement for element 2 and so on. The average brightness, u, trends upwards as each element is optimized.

where v is the motion parameter and t tracks the absolute time that the brightness measurements are taken. In the simplest case, repeating a given measurement (τ fixed) at different times t enables v to be determined and the drift removed from all other measurements. More generally, linear motion trends can be removed from the 3-shot solution described above with one additional shot resulting in the linear system

$$\begin{bmatrix} B_1(\tau_1;t_1) \\ B_2(\tau_2;t_2) \\ B_3(\tau_3;t_3) \\ B_4(\tau_4;t_4) \end{bmatrix} = \begin{bmatrix} 1 & t_1 & \cos(2\pi f_o\tau_1) & \sin(2\pi f_o\tau_1) \\ 1 & t_2 & \cos(2\pi f_o\tau_2) & \sin(2\pi f_o\tau_2) \\ 1 & t_3 & \cos(2\pi f_o\tau_3) & \sin(2\pi f_o\tau_3) \\ 1 & t_4 & \cos(2\pi f_o\tau_4) & \sin(2\pi f_o\tau_4) \end{bmatrix} \begin{bmatrix} u \\ v \\ A\cos\phi \\ A\sin\phi \end{bmatrix} \tag{5}$$

which is fully determined for ϕ. By keeping track of absolute inter-element measurement times and employing one additional shot, motion compensation can also be applied to the 2-shot solution described above. Additional measurements allow motion that is higher-order than linear to be compensated.

III. Experimental Verification

The software of a Philips iE33 ultrasound scanner was modified to verify the ability of N-shot algorithms to correct delay aberrations. Figure 4 shows an example of one such correction. In this case the 2-shot algorithm was used to correct the image of a phantom made using an S5-1 phased array with a 1-D artificial aberrator (pictured in Fig. 8 of [10]) attached.

Correction using the delays calculated by the 2-shot algorithm clearly improves the anechoic cyst and lesion contrasts and reduces the sidelobes from the wire targets. The improvement does not extend over the whole image however. In this example, the delay values obtained from a single ROI were applied to the entire image. Evidently, even the relatively thin aberrator used in this experiment is isoplanatic over only about $30°$ of the $90°$ field of view.

The Fig. 4 results were obtained with a 25 line by 11 mm ROI and there were three (look-back) passes across the array. Similar improvements could be routinely obtained with ROIs containing as few as one or two lines (in which case correction times on the order of tens of ms are possible). Most of the improvements were obtained in the first pass across the array and 2-shot and 3-shot were found to provide substantially equivalent improvements.

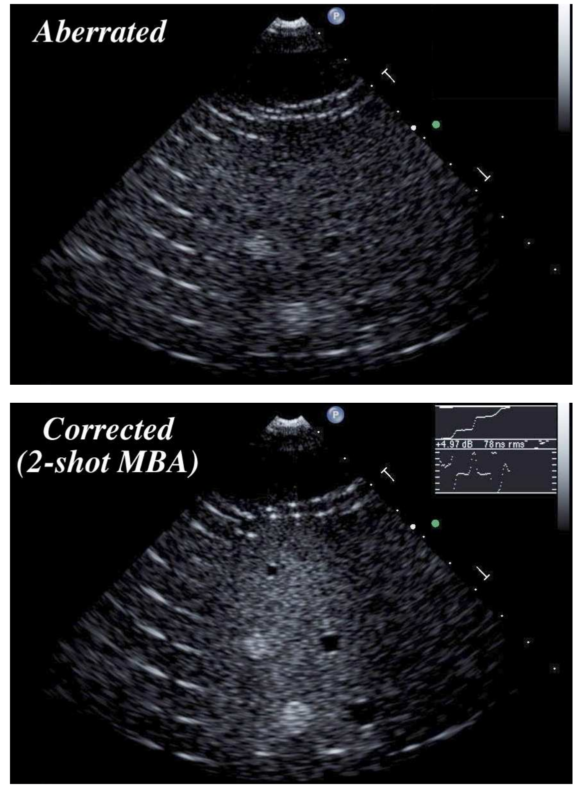

Fig. 4. Experimental demonstration of the 2-shot maximum brightness algorithm correcting an image of a phantom made using a phased array with artificial aberrator attached. Brightness gain (upper trace in insert) is 4.97 dB. Aberration profile (lower trace in insert) has a standard deviation of 78 ns (although this number likely underestimates the true value because of “phase wraps”).

IV. Conclusions

N-shot is an alternative to the previously published iterative maximum brightness algorithm for delay aberration correction. Based on the empirical observation that the average speckle brightness exhibits a nearly sinusoidal variation with respect to any one element’s beamformer delay, N-shot uses curve fitting rather than an iterative search.

N-shot is much more efficient than iterative MBA. The number of brightness measurements needed to correct one element, N, can be as low as two. Furthermore, with N-shot MBA, N is constant. Adaptation times are completely predictable, which is useful in practical system design. For example, the 2-shot algorithm operating on an ROI located at 8 cm could correct an entire 64-element array in 13 ms (plus system overhead). The speed does not depend on the delay quantization.

Iterative MBA compares the brightness changes that result from incrementing beamformer delays by small steps. However, the brightness changes relatively slowly in the neighborhood of the optimal delay (recall that a sinusoid has zero slope at its peak). In practice, thermal and motion noise can easily overwhelm these relatively small brightness changes, causing the search to halt prematurely before the true maximum is found. The problem is exacerbated as the delay resolution increases.

In contrast, N-shot MBA is relatively robust to thermal and motion noise for several reasons: Brightness measurements are taken at widely separated beamformer delays so that the brightness changes are comparatively large and therefore relatively unaffected by noise. If desired, additional shots can be employed to (a) over-determine the solution and reduce sensitivity to thermal noise and/or (b) directly solve for the motion noise. The inherent robustness to thermal noise allows fewer lines to be used in the ROI. This further reduces adaptation time and may also reduce sensitivity to motion noise. In addition, the smaller ROI improves performance in the presence of non-isoplanatic aberrators. These advantages are independent of the delay resolution.

Finally, we note that, in common with correlation-based aberration correction methods, N-shot MBA is still limited by the near-field phase-screen assumption (the validity of which has been called into question by direct in-vivo measurements [11]). Further experimental work is required to establish the clinical value of N-shot MBA.

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