Published in final edited form as:

IEEE Trans Ultrason Ferroelectr Freq Control. 2010 January ; 57(1): 214–228. doi:10.1109/TUFFC.2010.1400.

A Model of Distributed Phase Aberration for Deblurring Phase Estimated from Scattering

Jason C. Tillett, Jeffrey P. Asstheimer, and Robert C. Waag [Life Fellow, IEEE]

The authors are with the Department of Electrical and Computer Engineering, University of Rochester, Rochester, NY

Jason C. Tillett: tillett@ece.rochester.edu

Abstract

Correction of aberration in ultrasound imaging uses the response of a point reflector or its equivalent to characterize the aberration. Because a point reflector is usually unavailable, its equivalent is obtained using statistical methods, such as processing reflections from multiple focal regions in a random medium. However, the validity of methods that use reflections from multiple points is limited to isoplanatic patches for which the aberration is essentially the same. In this study, aberration is modeled by an offset phase screen to relax the isoplanatic restriction. Methods are developed to determine the depth and phase of the screen and to use the model for compensation of aberration as the beam is steered. Use of the model to enhance the performance of the noted statistical estimation procedure is also described. Experimental results obtained with tissue-mimicking phantoms that implement different models and produce different amounts of aberration are presented to show the efficacy of these methods. The improvement in b-scan resolution realized with the model is illustrated. The results show that the isoplanatic patch assumption for estimation of aberration can be relaxed and that propagation-path characteristics and aberration estimation are closely related.

I. Introduction

Ultrasound b-scan images are commonly used for medical diagnosis. However, the quality of these images can be degraded by aberration from tissue in the propagation path between the transmitter-receiver combinations and the anatomic features that are being imaged. Consequently, considerable research has been aimed at ways to characterize or measure the aberration and to then use the characterization of aberration to compensate for the aberration [1]–[8].

Interest in describing and correcting aberration in optical imaging predates the concern for these issues in ultrasound imaging applications. The optical literature, see e.g., [9] and [10], suggests use of point-response measurements to characterize aberration. In optical systems, point-responses are usually obtained by imaging point sources. Stars in telescopic images are a noteworthy example. In ultrasound imaging systems, point responses may also be obtained from point-like reflectors when they are available.

Coherent point responses are particularly useful in ultrasound systems that are comprised of extended arrays of transducer elements. Signals that arrive at the array from a point reflector in a medium without excessive attenuation may be time-reversed and retransmitted to

produce a focus at the reflector that is uncorrupted by the medium aberrations. These retransmitted signals appear to use the intervening medium as a lens that produces a better focus than could be obtained with homogeneous transmission [11]–[13]. Frequency decomposition of point-reflector responses also yields phase that produces uncorrupted focuses of monochromatic transmissions at the reflector. Furthermore, geometric adjustment of the phase permits a high quality focus to be repositioned at neighboring locations as long as the aberration experienced *en route* to the new positions remains substantially the same as the aberration for the original point reflector. A neighborhood of points that share the same aberration is called an isoplanatic patch or isoplanatic region. Isoplanatic regions are related to tissue characteristics as well as measurement geometry and have been found to be larger along the axis of a transducer array than in lateral directions [14].

Point reflectors are usually not available in medical applications. Fortunately, point-reflector responses can also be obtained from cross-spectral measurements of random media by using a statistical method that is described in [15]. In this method, echo signals are acquired from a collection of focuses in random-medium patches that are within a single isoplanatic region. The focuses for these measurements must be far enough apart to ensure a degree of statistical independence but are constrained in space by the isoplanatic requirement.

Thus, isoplanatic regions are limiting factors for aberration correction in 2 respects: they limit the region over which retransmission of point-response measurements can be used to recover an uncorrupted focus, and they limit the span of focal points needed in statistical measurements to estimate impulsive responses. The purpose of this study is to reduce these restrictions by allowing aberration to vary in a deterministic manner. Specifically, monochromatic aberration is modeled by a phase screen that is located at an intermediate distance between the transducer array and the focal region. The offset location of the phase screen introduces variations in the aberration for neighboring focal points because rays from the transducer elements to different focal points intercept the phase screen at different locations. This paper shows that by placing the phase screen at an appropriate depth, the variations that are introduced can model the true aberration across an area that is significantly larger than the isoplanatic region. In fact, the usual definition of isoplanatic region may be viewed as the range of accuracy for the special case of the model in which the phase screen is located in the same plane as the transducer array.

Offset phase screens have been shown to be an applicable model for improving focus compensation in human abdominal wall [8]. In that work, backpropagation of the received wavefront to the phase screen location using the angular spectrum method provided better compensation calculated using the single, backpropagated wavefront. In this work, backward and forward propagation is along rays to correct for lateral shifts in the phase screen as the focus is steered to generate the many wavefronts that are required to implement a statistical estimation of the compensation factors.

The theory section in this paper explains how to incorporate the depth of the phase screen when correcting for aberration, how the statistical procedure for point-response estimation can be modified to accommodate an offset phase screen, and how the depth of the phase screen is estimated. In the section that follows, the theory is validated by measurements made with a custom 2-D transducer array in a temperature-controlled water-tank. The results of the measurements are summarized and their significance discussed in succeeding sections. Finally, a set of conclusions is drawn from the investigations.

II. Theory

A. Offset Phase-Screen Model for Aberration

A measurement geometry in which the z -axis coincides with the axis of a 2-D transducer array located in the $z = z_T$ plane as shown in Fig. 1 is considered. In this geometry, let $\varphi^0 = (\mathbf{x}, z; \mathbf{x}_0, z_0)$ denote the monochromatic field that propagates homogeneously with wavenumber k from a point reflector at $(\mathbf{x}_0, z_0)$ and let $\varphi(\mathbf{x}, z; \mathbf{x}_0, z_0)$ be the corresponding field that propagates through aberration. Measurement of the inhomogeneous field across the transducer array gives values for $\varphi(\mathbf{x}_T, z_T; \mathbf{x}_0, z_0)$ in a rectangle of the $z = z_T$ plane. The aberration within that rectangle can be characterized by the phase term

$$\alpha(\mathbf{x}_T, z_T; \mathbf{x}_0, z_0) = \text{Phase} \left[\varphi(\mathbf{x}_T, z_T; \mathbf{x}_0, z_0) / \varphi^0(\mathbf{x}_T, z_T; \mathbf{x}_0, z_0) \right]. \quad (1)$$

This phase can be used to produce a high-quality monochromatic focus at $(\mathbf{x}_0, z_0)$ by applying the complex transmission amplitude

$$\overline{\varphi^0(\mathbf{x}_T, z_T; \mathbf{x}_0, z_0)} e^{-j\alpha(\mathbf{x}_T, z_T; \mathbf{x}_0, z_0)} = \overline{\varphi(\mathbf{x}_T, z_T; \mathbf{x}_0, z_0)} \quad (2)$$

to the array. If the point $(\mathbf{x}_1, z_1)$ is in the same isoplanatic patch as $(\mathbf{x}_0, z_0)$, then

$$e^{-j\alpha(\mathbf{x}_T, z_T; \mathbf{x}_1, z_1)} \approx e^{-j\alpha(\mathbf{x}_T, z_T; \mathbf{x}_0, z_0)} \quad (3)$$

and a high-quality focus can also be produced at $(\mathbf{x}_1, z_1)$ by using the transmission amplitude

$$\overline{\varphi^0(\mathbf{x}_T, z_T; \mathbf{x}_1, z_1)} e^{-j\alpha(\mathbf{x}_T, z_T; \mathbf{x}_0, z_0)}. \quad (4)$$

The phase of the first factor in (4) provides geometric focusing that is used to steer the focus, and the second factor compensates for aberration.

Unfortunately, the accuracy of the approximation in (3) diminishes quickly as the separation between points $(\mathbf{x}_1, z_1)$ and $(\mathbf{x}_0, z_0)$ increases, particularly in the lateral direction. However, aberration can be modeled in a way that is more tolerant of the separation between source points by assuming that the aberration takes place in a plane that lies between the focal region and the transducer array. Thus, aberration is represented by a phase screen $e^{j\theta}(\mathbf{x}_{sc}, z_{sc})$ in a plane $z = z_{sc}$, where $z_T \leq z_{sc} \leq z_0$. If the approximations of geometric optics are applied to the model, then the phase factors at each point in the screen only influence rays that pass through that point. This geometry is illustrated in Fig. 1.

Ray approximations permit determination of the screen phase $\theta(\mathbf{x}_{sc}, z_{sc})$ from the aberration phase $\alpha(\mathbf{x}_T, z_T; \mathbf{x}_0, z_0)$ given by (1). The result is

$$\theta(\mathbf{x}_{sc}, z_{sc}) = \alpha(P_{\text{screen}}[\mathbf{x}_{sc}, z_{sc}; \mathbf{x}_0, z_0]; \mathbf{x}_0, z_0), \quad (5)$$

where $P_{\text{screen}}[\mathbf{x}_{sc}, z_{sc}; \mathbf{x}_0, z_0]$ is the projection

$$P_{\text{screen}}[\mathbf{x}_{sc}, z_{sc}; \mathbf{x}_0, z_0] = \left[\mathbf{x}_0 + \left(\frac{z_T - z_0}{z_{sc} - z_0} \right) (\mathbf{x}_{sc} - \mathbf{x}_0), z_T \right] \quad (6)$$

of the point $(\mathbf{x}_{sc}, z_{sc})$ in the phase screen onto the transducer plane along the ray that originates at $(\mathbf{x}_0, z_0)$ (i.e., along the dashed line in Fig. 1).

The inverse of this projection maps points on the transducer plane onto the phase screen. This inverse is given by

$$\begin{aligned} (\mathbf{x}_{sc}, z_{sc}) &= P_{\text{screen}}^{-1}[\mathbf{x}_T, z_T; \mathbf{x}_0, z_0] \\ &= \left[\mathbf{x}_0 + \left(\frac{z_{sc} - z_0}{z_T - z_0} \right) (\mathbf{x}_T - \mathbf{x}_0), z_T \right]. \end{aligned} \quad (7)$$

Substitution of the inverse projection in place of the $(\mathbf{x}_{sc}, z_{sc})$ arguments in (5) gives

$$\alpha(\mathbf{x}_T, z_T; \mathbf{x}_0, z_0) = \theta(P_{\text{screen}}^{-1}[\mathbf{x}_T, z_T; \mathbf{x}_0, z_0]). \quad (8)$$

Eq. (8) determines the phase compensation for the focal point $(\mathbf{x}_0, z_0)$ from the phase screen.

The factors $e^{-j\alpha(\mathbf{x}_T, z_T; \mathbf{x}_0, z_0)}$ and $e^{-j\alpha(\mathbf{x}_T, z_T; \mathbf{x}_1, z_1)}$ that are needed to compensate the focus at the neighboring points $(\mathbf{x}_0, z_0)$ and $(\mathbf{x}_1, z_1)$ are given by

$$e^{-j\alpha(\mathbf{x}_T, z_T; \mathbf{x}_0, z_0)} = e^{-j\theta(P_{\text{screen}}^{-1}[\mathbf{x}_T, z_T; \mathbf{x}_0, z_0])} \quad (9)$$

and

$$e^{-j\alpha(\mathbf{x}_T, z_T; \mathbf{x}_1, z_1)} = e^{-j\theta(P_{\text{screen}}^{-1}[\mathbf{x}_T, z_T; \mathbf{x}_1, z_1])}, \quad (10)$$

and are no longer equal except in the special case in which the phase screen is in the plane of the transducer.

B. Statistical Estimation of Aberration for an Offset Phase Screen

As noted in the introduction, point reflectors are usually not available in ultrasound imaging but can be simulated by a statistical process that uses focused measurements from a collection of patches of random media sharing the same aberration. The original development of this technique in [15] required the aberration to be the same in the sense that the focal points $(\mathbf{x}_1, z_1)$, $(\mathbf{x}_2, z_2)$, ..., $(\mathbf{x}_n, z_n)$ for all the measurements had to belong to the same isoplanatic region. This is a restrictive condition that may also be expressed as

$$\alpha(\mathbf{x}_T, z_T; \mathbf{x}_j, z_j) = \alpha(\mathbf{x}_T, z_T; \mathbf{x}_k, z_k), \quad j, k = 1, 2, \dots, n. \quad (11)$$

The offset phase screen model can be used to lessen this constraint. This is accomplished by applying the statistical computations to measurements that have been back-propagated from the face of the transducer array to the plane of the phase screen. According to the model, the aberration for the measurements is different in the transducer plane but is the same in the plane of the phase screen. The condition given in (10) can then be replaced by the relaxed requirement that the aberration for all the focal points is accurately modeled by a single offset phase screen.

In practice, this approach can be further simplified by only backpropagating the phase of the measured fields and by using (5) to backpropagate along rays, consistent with the assumptions that the phase information is of paramount importance in aberration correction

and that phase variations are accumulated along rays. Although the details of the statistical computations are not important here, it is noteworthy that aberration estimates are computed iteratively so that improved estimates can be used to produce better focuses and more accurate beam-steering in successive computations. The offset phase-screen model can help to accelerate the convergence of these iterations by employing aberration phase corrections that vary with the focal point rather than adhering to a single fixed correction for all the focal points.

C. Determination of the Offset Phase-Screen Depth

The previous subsections have described methods for assigning phase variations to the phase screen. They have also explained how the offset phase screen model can be used to compensate for aberration when the focus is directed toward different locations. This subsection explains how the depth of the phase screen can be established from experimental measurements.

The depth of the phase screen can be derived from a pair of point-reflector measurements provided that the locations $(\mathbf{x}_0, z_0)$ and $(\mathbf{x}_1, z_1)$ of the reflectors are known, that $\mathbf{x}_0$ and $\mathbf{x}_1$ are close to one another, and that the 2 points are at roughly the same depth (i.e., $z_1 \approx z_0$). Factoring the homogeneous field from these measurements and extracting the phase, as in (1), leaves the terms $e^{j\alpha(\mathbf{x}_T, z_T; \mathbf{x}_0, z_0)}$ and $e^{j\alpha(\mathbf{x}_T, z_T; \mathbf{x}_1, z_1)}$. The offset phase screen model predicts that these terms are given by

$$e^{j\alpha(\mathbf{x}_T, z_T; \mathbf{x}_0, z_0)} = e^{j\theta(P_{\text{screen}}^{-1}[\mathbf{x}_T, z_T; \mathbf{x}_0, z_0])} = e^{j\theta(\mathbf{x}_0 + \lambda(\mathbf{x}_T - \mathbf{x}_0), z_T)} \quad (12)$$

and

$$e^{j\alpha(\mathbf{x}_T, z_T; \mathbf{x}_1, z_1)} = e^{j\theta(P_{\text{screen}}^{-1}[\mathbf{x}_T, z_T; \mathbf{x}_1, z_1])} = e^{j\theta(\mathbf{x}_1 + \lambda(\mathbf{x}_T - \mathbf{x}_1), z_T)}, \quad (13)$$

where $\lambda = (z_{\text{sc}} - z_0)/(z_T - z_0) = (z_{\text{sc}} - z_1)/(z_T - z_1)$.

The expressions on the right side of (12) and (13) can be used to write the correlation of the measurements as

$$\int e^{j\alpha(\mathbf{x}_T + \mathbf{y}, z_T; \mathbf{x}_0, z_0)} e^{-j\alpha(\mathbf{x}_T, z_T; \mathbf{x}_1, z_1)} d^2 \mathbf{x}_T = \int e^{j\theta(\mathbf{x}_1 + \lambda(\mathbf{x}_T - \mathbf{y} - \mathbf{x}_1), z_T)} e^{-j\theta(\mathbf{x}_0 + \lambda(\mathbf{x}_T - \mathbf{x}_0), z_T)} d^2 \mathbf{x}_T. \quad (14)$$

The integral on the right side of (14) is clearly maximum when

$$\mathbf{y} = \frac{1 - \lambda}{\lambda} (\mathbf{x}_1 - \mathbf{x}_0) = \frac{z_T - z_{\text{sc}}}{z_{\text{sc}} - z_0} (\mathbf{x}_1 - \mathbf{x}_0). \quad (15)$$

Taking the norm of both sides of (15) and solving for z_{sc} gives

$$z_{\text{sc}} = \frac{\|\mathbf{x}_1 - \mathbf{x}_0\|}{\|\mathbf{x}_1 - \mathbf{x}_0\| + \|\mathbf{y}\|} z_T + \frac{\|\mathbf{y}\|}{\|\mathbf{x}_1 - \mathbf{x}_0\| + \|\mathbf{y}\|} z_0. \quad (16)$$

Eq. (16) determines the depth of the phase screen from the magnitude $\|\mathbf{y}\|$ of the offset for the peak value of the correlation function for the measurements from the 2 point reflectors.

When point reflectors are unavailable, the measurements needed to estimate the phase-screen depth can also be obtained from statistical estimates formed from random media (simulated point responses) [15]. Simulation of point responses can utilize subsets of focal points as well as iteration for improving the quality of the estimated phase. Experience indicates that screen-depth calculations do not seem to require high-quality simulated-point-response measurements. Thus, the screen depth can generally be established using fewer focal points and fewer (or no) iterations of the simulated-point-response estimates.

III. Methods

Data sets were acquired using a large 2-D array system [16] comprised of 80×80 transducer elements with a $0.6 \times 0.6 \text{ mm}^2$ pitch. The system operates at a center frequency of 3 MHz and has a -6-dB transmit-receive bandwidth of 1.8 MHz. The received signals are digitized with 12 bits of resolution at a sampling rate of 20 MHz. The transmitted waveforms are programmable. The array elements are independently compensated with gain factors that were determined using the calibration procedure described in [17].

A. Aberration-Phase Maps and Time-Shift Maps

1) Aberration-Phase Maps and Time-Shift Maps for Point-Reflector

Measurements—Point-reflector experiments were used to form ideal profiles of aberration phase that serve as standards for comparison with the aberration phases derived from random scattering. The point reflections were produced by the tip of a 0.2-mm polyvinylidene fluoride (PVDF) needle probe hydrophone placed at a transmit focus located 55 mm below the center of the transducer array. The initial approximate positioning of the hydrophone was adjusted using high-precision stepper motors that were guided by pulse-echo measurements. This allowed the depth and the lateral location of the tip of the hydrophone to be assigned with an accuracy of $\pm 0.01 \text{ mm}$. A hydrophone was used as the point reflector so that measurements of compensated focuses could be performed without having to move anything that could cause additional shifts in measured phase.

The wavefronts of measured reflections from the hydrophone have curvatures characteristic of highly localized scattering. Reflections that were received through the water path had perfectly spherical wavefronts. However, reflections that were received through aberrators deviated from the ideal spherical shape. Cancellation of these phase deviations in the Green's function by using compensating phases is necessary to produce a high-quality focus.

A tissue-mimicking aberrator was inserted between the transducer and the hydrophone and pulse-echo measurements were acquired. Phases of the Fourier coefficients of the received signals at each temporal frequency form a map across the transducer array of the wavefront for the monochromatic reflections at that frequency. Phases of the perfectly spherical wavefronts that occur in the absence of aberration (i.e., in the water path) were subtracted from the phase maps from measurements that were formed through aberration to isolate the phase deviations directly attributable to aberration. This computation produced aberration-phase maps for each temporal frequency. Compensation for aberration was accomplished by applying phases that are the conjugate of the aberration-phase maps for each Fourier coefficient of each received signal. This provided a distinct compensating factor for each frequency and each transducer element. However, the aberration-phase maps were very nearly linear in frequency and, hence, could be approximated using a single time-shift map in which the time shift at each element was the slope of the phase variation with frequency. Such time-shift maps across the transducer array represent arrival-time fluctuations (ATF) from an expected spherical geometry and were derived from the phase maps by forming linear fits to the unwrapped phases at each transducer element. The phase unwrapping employed in this time-shift estimation was performed in 3 dimensions (2 dimensions

spanning the transducer array and the third dimension spanning temporal frequency) rather than separately unwrapping the phase variations with temporal frequency at each element because unwrapping is more robust in higher dimensions.

2) Aberration-Phase Maps and Time-Shift Maps for Random-Scattering

Measurements—The experimental configuration for random-scattering experiments was the same as that for the point-reflector experiments except that a random-scattering phantom was used in place of the hydrophone. Transmit beams were geometrically focused at 11 points that were a subset of 75 points defined by the center and vertices of the 3 concentric Platonic figures that were used as focuses in [15]. These 75 points were chosen as focuses in the earlier study to optimize the statistical independence of the scattering samples while staying within a designated isoplanatic region [18]. The subset of vertices selected for the focuses in the current study consists of the center of the solids together with the 10 vertices with depths that are closest to the depth of the center focus. (See Fig. 2.) These vertices were chosen because they are all located at roughly the same depth and because reflections from these locations produced aberration-phase maps that are maximally shifted relative to one another. Spherical geometry associated with propagation in a water path was removed from the signals received from each focus. A temporal window determined from average sound speeds for the aberrator and the phantom was applied to the signals to select random-medium reflections that were arriving from the focus location. Estimates of aberration phase are relatively insensitive to the placement of this window because the axial size of an isoplanatic patch is typically much larger than its lateral extent. The windowed and geometrically corrected signals were used to form statistical estimates of the aberration phase as described in [15]. Again, time-shift maps were formed from the phase estimates.

B. Estimation of Phase-Screen Depth

The depth of the phase screen determines the way predicted values for aberration-phase factors vary for focuses formed at different locations. Screen-depth estimates are based on detecting parallax in the phase maps or time-shift maps of neighboring sources. This effect can be observed in any pair of phase maps or time-shift maps for neighboring sources. Consequently, depth estimates can be formed from any pair of point-reflector measurements. However, each phase map or time-shift map obtained from random-scattering measurements must be statistically estimated from measurements for an entire set of focuses. Thus, detection of parallax in random-scattering measurements requires statistical estimates from 2 distinct sets of focuses.

Statistical methods that rely on time-varying media rather than neighboring focuses [19] can be used to form estimates of offset time-shift screens and offset-phase screens without having to backpropagate the signals to the plane of the screen. The screen depth is only used in these cases to adjust the compensation factors as the beam is steered to different locations. However, estimating the depth of the phase screen still requires a parallax calculation based on statistical estimates from at least 2 neighboring locations.

1) Phase-Screen Depth Estimates from Point-Reflector Measurements—Point-reflector experiments were performed with the hydrophone located at each of the 11 focuses that were selected for the random scattering experiments. Aberration-phase maps were computed for each of these focuses as described in Section III-A. A total of 55 ways exist to pair measurements from different locations. However, in 27 of these pairs, the lateral separation of the reflectors is less than 1.5 mm. This makes the parallax effect difficult to discern. Therefore, estimates of the screen depth were only computed for the other 28 pairs. For each pair, the 2.5-MHz (near center frequency of the system) phase maps for the focuses were cross correlated, as in (14), and the spatial shift of maximum correlation was found.

The screen depth was estimated by applying (16) to this spatial shift. Estimates of the screen depth were also obtained from the positions of the cross correlation peaks for each of the 28 pairs of time-shift maps.

2) Phase-Screen Depth Estimates from Random-Scattering Measurements—

Random-scattering measurements were obtained from 2 sets of focuses with each set surrounding one of the 2 simulated source locations as shown in Fig. 2. A more localized cluster of focuses was used than was used in estimating the phase screen to avoid blurring of the parallax effect that could result from larger lateral displacements. Each set of focuses consisted of the center and vertices of the smallest of the 3 Platonic solids (an icosahedron) whose vertices were identified in [18] as optimal locations for the focuses within an isoplanatic patch with an expected size of 3 mm. Use of this more concentrated cluster of focuses permitted the formation of 2 disjoint sets of scattering volumes that were separated by less than the size of the isoplanatic patch.

Random-scattering experiments contrast with point-source experiments in that the precise location of the source is unknown and, consequently, the exact source geometry cannot be removed from the estimated phase maps. Instead, the methods detailed in [20] were used to fit an apparent focus location and the geometry for this fitted location was removed. An alternative approach would be to use iterative methods like those detailed in Section III-D to make successive refinements in the source location. However, because the objective was to estimate a single parameter, i.e., the screen depth, a more expeditious computation was employed. After the fitted geometry was removed, mean positions of the 2 source locations were calculated. Time-shift maps were formed from the statistical phase maps and depth estimates were derived in the same way as described for point-source experiments.

C. Compensation of Focused Beams Using Estimated Phase

The tip of the PVDF hydrophone was positioned under the 2-D array using the alignment technique described in Section III-A. Aberration-phase maps from this point reflector were measured. These phases were used to compensate a transmit beam focused at the same location. The hydrophone was then used to sample values of the amplitude of the focus at different locations. These amplitudes were initially scanned in the axial direction of the transducer array to find the location of the peak intensity. The focus was then scanned along the 3 axes of an orthogonal coordinate system in which one of the axes was perpendicular to the transducer array (i.e., depth) and the other 2 lateral axes were oriented along directions defined by the grid of transducer elements. The position of the origin of the lateral axes was directly below element (40, 40), the center element of the 2-D array. Samples of the focus amplitude in the axial direction were taken in 0.5-mm increments over a span of 10 mm centered at the origin. Samples of the focus in the lateral direction were taken in 0.2-mm increments over a span of 10 mm, also centered at the origin. Measurements were obtained from transmit subapertures and the total field at each hydrophone position was computed by summing all subaperture measurements. Corresponding measurements of the focus were obtained for focused beams that were steered away from the center-focus position without changing the transmit compensation.

In Section II, ray-propagation arguments were described to obtain phase compensations from the offset phase-screen model for focused beams that are steered to different locations. These compensations are effective at focal points that are outside of the isoplanatic patch used to determine the phase screen. The compensating phases for each focal point are theoretically obtained from a projective transformation of the phase screen onto the surface of the transducer array along rays that emanate from the focal point as illustrated in Fig. 3. However, projective transformations of a discretely sampled phase screen produce values in the plane of the transducer array that are sampled at locations that do not coincide with the

transducer elements so phase compensation values at the element locations must be interpolated. To perform this assignment, Fourier interpolation was employed. These compensations were applied to beams steered to other locations and the focus was measured at these locations to quantify focus improvement.

D. Estimation of the Offset Phase Screen from Random Scattering

Random scattering was produced by a tissue-mimicking random-scattering phantom positioned beneath the aberrator in place of the hydrophone used for the point-reflector experiments. Measurements were acquired for the scattering from each of the 11 transmit focuses identified in Section III-A.

Propagation of the transmit beams through the aberrator can result in unknown shifts of the focuses away from their intended locations. Shifts of this type are not important in point-reflector measurements because the phase variations for these measurements only depend on the location of the reflector. However, the focal points for random scattering measurements are carefully chosen to balance the need for statistical independence and the need for the aberration associated with all the focuses to be accurately modeled by a single phase screen. Thus, drift in the transmit focuses can have undesirable effects on aberration estimates derived from random scattering.

The iterative procedure summarized in Fig. 4 was employed to reduce drift in the transmit focus. The initial transmissions were geometrically focused, without any compensation, at each of the 11 focuses. Successive transmissions were focused with compensation derived from the offset phase screen estimated from the measurements of the previous step. Offset phase screens were obtained by first backpropagating the Fourier phase of the received signals along rays from the transducer array to the phase screen. The backpropagated signals were then employed to form a statistical estimate of the phase screen by using the estimation procedure described in [15]. Iterations of the procedure were repeated until the differences in the phase screen estimates for successive iterations were no longer significant. Iteration was evaluated for some of the aberration estimates formed from random scattering. In these cases, almost all the improvement was realized in the first iteration.

Successful correction of focus dislocation was verified using the procedure detailed in [20]. This method requires the selection of time-gates to localize the geometry. Choosing an appropriate time-gate for point-reflector measurements is straightforward and may be based on visual inspection of the signals, but the echos from the random media focus are not as easy to identify. The time gates for the random medium reflections were, therefore, determined by using the known average sound speeds of the aberrator and phantom to calculate the arrival time of echoes from the focus. When a known object, like a scatterer-free sphere, is in the focal region this method produces time gates consistent with time gates that would be assigned using visual inspection of the received echoes.

E. Experiments

Four aberrators were studied. Their properties are summarized in Table I. These aberrators were designed to simulate effects of ultrasound propagation in tissues. They were made by Computerized Imaging Reference Systems, Inc., Norfolk, VA (CIRS) and were selected to represent a variety of aberration geometries and aberration strengths. Magnetic resonance images of the aberrators are shown in Fig. 5. These vertical cross sections are near the center of the field through which the ultrasound signals were propagated. The magnetic resonance images show differences in the way that the aberration is distributed. In Aberrators 4491 and 6277, the inclusions are generally closer to the transducer array. In Aberrators 6289 and

4064, the inclusions are farther away. There are also differences in the amount of variation in the depth of the inclusions.

Aberrator strengths were characterized by computing standard deviations of the arrival time fluctuations of signals from point sources, as detailed in [20]. In Table II, the aberrators are categorized by aberration strength estimates for point sources that were positioned near the lateral centers of the aberrators.

1) Measurement of Improvement in Phase Predictions and Time-Shift

Predictions—Aberration-phase maps at 2.5 MHz were obtained from point-reflector experiments using each of the 11 reflector positions described in Section III-A. A phase screen was then produced by back-propagating the phase map for the center focus along rays, as described in Section II-C, to the screen depth that was estimated and described in Section III-B. Aberration-phase maps were then computed for each of the focuses as phase-screen projective transformations (Eq. 8).

Videos were produced for each of the 4 aberrators (, , ,). The videos show gray-scale images of measured aberration-phase maps together with aberration-phase maps that were projected from the phase screen. In these videos, the position of the focus changes from frame to frame. The (unchanging) aberration-phase map for the center focus also appears in a separate panel. This stationary phase map may be interpreted as the projection of a phase screen that is located at the depth of the transducer array because all projective transformations are identity maps when the screen depth is zero.

The videos provide visual comparisons of the aberration modeled by an offset phase screen with the aberration modeled by a phase screen that is not offset. Two of the lower panels in the video contain gray-scale images of the differences between measured aberration phase and the aberration that is predicted by each of the 2 phase screens (i.e., the offset phase screen and the phase screen with no offset). A mean and a standard deviation are reported for each of these images. The standard deviations are averaged over the focus positions (i.e., over the frames of the video) to obtain a single parameter for each of the 2 phase-screen models that measures how well the model is able to predict the aberration-phase maps for the different focuses.

Time-shift maps were also computed from point-reflector experiments for each of the reflector positions using the method described Section III-A. The time shifts for the center focus were backpropagated along rays to the screen depth that was estimated in Section III-B to produce an offset time-shift screen. Time-shift maps were then computed for each of the focuses as projective transformations of the time-shift screen. The accuracy of these predictions was compared with the accuracy of time shifts that were predicted by a time-shift screen with no offset (i.e., the unchanging time shifts of the center focus) using the same standard-deviation calculation that was described above for comparison of phase predictions.

2) Measurement of Improvement in Focus—Phase screens for these experiments were estimated from point-reflector experiments. The phase-screen depth was determined as described in Section III-B. The 2.5-MHz phase map for the reflection from the center focus was used as a zero-offset phase screen. A second phase screen at the estimated depth was obtained by applying the statistical estimation procedure described in [15] to signals from the point-reflector experiments that were backpropagated along rays to that depth.

Both phase screens were used to obtain phase compensations for transmit beams that were focused at the location of the center focus and also at an offset location that was 1.5 mm

away from the center focus. A hydrophone was used to sample the amplitudes of these focuses in the vicinity of the focal points. Plots of the effective radii of the focuses were found, as described in [21], from these measurements.

3) Measurement of Improvement in B-Scan Contrast—A scatterer-free cyst-mimicking region was imaged with no compensation and also with compensation derived from both an offset phase screen and a phase screen with no offset. The offset phase screen was estimated from random scattering using the iterative process described in Section III-D. The screen with no offset was estimated from random scattering using the statistical estimation procedure described in [15]. To scan the cyst-mimicking region, the 2-D array was linearly translated in 0.2-mm increments across the area of interest. This area contained the cyst-mimicking region that was 4 mm in diameter with its center located approximately 55 mm from the transducer. The array was translated a total of 3 mm to acquire 15 scan lines. Transmissions were geometrically focused before phase compensation was applied.

Signals received in the aperture were beamformed using coherent summation of aperture waveforms that were shifted in time to focus at the transmit focus position. The set of scan lines formed a 2-D image spanning the region of interest. Quantitative comparisons were made based on contrast ratios. These contrast ratios are expressed as differences, in decibels, between the mean intensities in subregions of the cyst-mimicking region and the background regions. These regions were 1.7 mm in diameter, a little over half the lateral extent of the scanned lines and smaller than the known 4-mm diameter of the cyst-mimicking scatterer-free region. The reference background regions were above and below the cyst-mimicking region to avoid bias from a time-gain compensation that was not perfectly flat.

IV. Results

A. Estimates of Phase-Screen Depth

The results of screen-depth estimates derived from the spatial shifts using (16) as described in Section III-B are reported in Fig. 6 and Fig. 7. Variations in the sizes of the error bars indicate that screen-depth estimates from the point-reflector phases are more reliable than estimates based on point-reflector time shifts. The screen-depth estimates derived from random scattering are only slightly shallower than the estimates from point-reflector experiments. This demonstrates that reliable estimates for the screen depth can be determined when point-reflector information is not available. All of the estimates reported in Fig. 6 are consistent with one another and also agree with visual impressions of where the phase screens should be located that are suggested by the magnetic resonance images of the aberrator cross sections in Fig. 5.

The effect of changes in the temporal frequency on the phase maps is shown in Fig. 7. Variations in temporal frequency appear to have little effect except at the lowest frequencies where the estimates have more variability. The frequency-dependent screen-depth estimates for Aberrators 6277 and 4064 generally have the smallest standard deviations. Because Aberrator 4064 has inclusions at a well-defined depth, the larger-than-expected standard deviation spread is because aberration is close to the focuses so that ray spreading that occurs between the aberration and the transducer array causes small depth variations to produce exaggerated spatial shifts. Thus, more error may be expected in screen-depth estimates for inclusions that are close to the focuses.

B. Accuracy of the Offset Phase-Screen Model

The phase maps projected from the offset phase screen are in closer agreement with the phase maps for the other focuses than the phase map for the unshifted center focus. To

quantify this improvement, standard deviations were computed for the images (that can also be viewed at the web site given by [22]) of the differences between the stationary phase map for the center focus and the phase maps of other focuses (i.e., the images shown in the lower center panel of each video). These standard deviations were averaged together to obtain a single number as a measure of the disparity between the phase map of the unshifted center focus and the phase maps for the other focuses. This calculation was repeated for the images of the differences between the phase map projected from the offset phase screen and the phase maps of other focuses (i.e., the images shown in the lower right panel of each video). The results of these calculations for each of the 4 aberrators are tabulated in Table III. Small portions of the difference images for Aberrator 6289 where the aberration was particularly severe were eliminated from the standard deviation calculations because aberration from these portions of the aberrator were not attributed to lateral shifts.

The standard deviations in Table III show that predicting aberration phase with an offset phase screen is better than relying on a phase screen in the plane of the transducer that does not change as the focus is relocated. The offset does not account for all the variations in aberration that occur as the focus is moved. However, a significant portion of the phase variability is clearly attributable to the offset.

These results indicate that each aberrator may be modeled by a set of phase screens (one for each frequency) or by a single time-shift screen at the prescribed depth. However, the estimated depth of the phase screen for a given experimental configuration is not the same as the intrinsic depth that locates the screen relative to the top surface of the aberrator. The intrinsic depth differs from the estimated depth by a flying distance to avoid contact between the shifting array and the stationary aberrator. The gap was kept as small as possible but large enough to ensure that shifts in the transducer across the surface of the aberrator would not cause the transducer to rub against the aberrator surface and damage the aberrator. The intrinsic phase-screen depths reported in Table III are obtained from the estimated depths by subtracting the flying distance for each set of experiments.

Once the phase-screen depth has been estimated, better agreement between phase maps at different focuses is obtained by propagating the aberration-phase maps backward along rays from the transducer array to the plane of the phase screen. This is because the offset phase-screen model is based on the assumption that backpropagated phase maps from different focuses will coincide at the depth of the phase screen. Fig. 8 shows the extent to which this assumption is satisfied for Aberrator 4064, which is the aberrator with the deepest phase screen. The upper-left panel is a gray-scale image of the time shifts that results from averaging together the time-shift maps for each of the focuses, and the upper-right panel is a gray-scale image of standard deviations for these averages. The bottom panels show corresponding images of the averages and standard deviations of the time-shifts obtained from phase maps that were backpropagated to the plane of the phase screen. Arrival-time fluctuations for the time-shifts derived from backpropagated phase maps were increased by almost 5 ns and the standard deviations of the arrival-time fluctuation for these time-shifts were reduced by more than 10 ns. The same analysis was performed for the other 3 aberrators and the results are summarized in Table IV.

The entries in the screen-depth column of Table IV give the depths used for backpropagation of the phase maps for the different aberrators. The aberrators in the table are in order of increasing phase-screen depth. The amounts of decrease in the standard deviations of the arrival time fluctuations that appear in the standard deviation decrease column are also increasing. This confirms the expectation that offset phase screens are more helpful for modeling aberration that is far away from the transducer array.

C. Improvement in Focusing

Fig. 9, obtained using Aberrator 4064, shows the effective-radius improvement that results in a focus obtained using an offset phase screen to compensate for aberration when the focus is steered to different locations. The curve labeled D (compensated with center-focus phase) shows the effective radial profile of a beam that is focused at the center focus with aberration compensation based on phase measurements from a point reflector at the same location. This curve may be viewed as the optimal focus that can be obtained through the aberrator. The curve labeled A (uncompensated) is an effective radial profile of a beam that is focused at the center focus without any compensation for aberration. The other 2 curves are effective radial profiles of focused beams that are steered to a neighboring location offset by 1.5 mm from the center focus. The curve labeled B (steered and compensated with the center-focus phase) is compensated for aberration by phase measurements from the point reflector at the center focus (i.e., by the same compensation as curve D). The radial profile labeled C (steered and compensated with the shifted center-focus phase) is compensated for aberration using phases that are derived from the offset phase screen that is obtained by backpropagating the point-reflector phases from the center focus to the screen depth that was estimated for the aberrator. These plots demonstrate that aberration corrections obtained from an offset phase screen can improve the focus of beams that are steered to different locations.

D. Improvement in Aberration Estimation

Improvement realized by statistical estimation of aberration by using offset phase screens is summarized in Fig. 10. The effective radial profiles of the focuses that are formed through the shallow screens of Aberrators 6277 and 4491 did not vary significantly for different compensations. In each case, the focus was restored to near water-path levels. However, compensation using offset-screen-model statistical estimates performed better than compensation using statistical estimates when focusing through the deep screens of Aberrators 6289 and 4064. The effective radial profile of the focus through Aberrator 6289 was nearly fully compensated down to the 30-dB level. Similarly, the offset-screen-model compensation restored water-path performance in Aberrator 4064 down to around the 20-dB level, and matched the performance of the center-focus compensation down to the 30-dB level.

E. Improvement in B-Scan Contrast

Aberrator 6289 was selected for investigating the improvement in b-scan images that can be realized by use of an offset phase-screen model to compensate for aberration. The inclusions in this aberrator are deeply situated and are modeled by a phase screen with a large offset that produces significant variations in the predicted aberration at different focuses. Furthermore, the compensated transmit focus for this aberrator that is shown in Fig. 10 has low sidelobe levels that should help to produce better image quality.

The 6 gray-scale images in Fig. 11 are created using the methods described in Section III-D. They are all b-scans that are 3-mm wide and are formed from 15 vertical scan lines. The b-scan on the left side of the figure (labeled uncomp) is obtained through the aberrator without any compensation on transmit or receive. The b-scan on the right side of the figure (labeled water) is obtained through a water path. The 4 b-scans in the middle of the figure are obtained through the aberrator with compensation. The b-scans labeled tx are formed using compensation for only the transmit focus and the b-scans labeled tx/rx are formed using compensation on both transmit and receive. The compensation for the scans labeled a is derived from a zero-offset phase screen that is statistically estimated from the phase maps of random scattering measurements. The compensation for the scans labeled b is derived from an offset phase screen that is statistically estimated from backpropagated phase maps of

random scattering measurements. Images formed with compensation factors predicted by the offset phase screen use new compensation factors for each scan line.

The improved performance of the offset phase-screen model evident in the images is quantified by computing contrast ratios for regions of special interest. The vertically-centered region in each image possesses the minimum mean intensity over each image and identifies the scatterer-free cyst-like region in the phantom. Regions for comparison are chosen above and below the vertically-centered region offset by the same amount in each image to avoid bias from time-gain compensation that is not perfectly flat. The offset is chosen also to avoid the specular reflections visible just above and below the vertically-centered region. The contrast ratio for the tx/rx image that is compensated using the offset phase screen is within 6 dB of the contrast ratio for the water-path image, whereas use of the zero-offset phase screen yields a contrast ratio that is about 14 dB away from the contrast ratio of the water-path image. The vertically-centered region can appear at different depths due to compensation. Also the average sound speed, that changes significantly when the aberrator is removed, can cause the vertically-centered region to shift as seen in the water-path b-scan.

V. Discussion

Screen-depth estimate differences that were obtained from point-source data and from the corresponding random medium data can be largely attributed to differences in experimental conditions. In point-source experiments, the aberrator was kept from 1 to 3 mm below the transducer to avoid deforming the aberrator. The additional offset was measured and the screen-depth estimates were adjusted accordingly to obtain depths that were relative to the top of the aberrator. However, in random-medium experiments, the presence of supporting material below the aberrator (i.e., the random medium phantom) allowed the transducer to be placed directly in contact with the aberrator. The transducer was, therefore, assumed to be positioned at the top of the frame that contains the aberrating medium (plastic retaining form open on the top and bottom) so no adjustments were made to the estimated screen depths. However, depressions in the surface of the aberrator that dip below the top surface of the retaining form still introduced small errors into the assumed height of the transducer. These errors translated into shallower relative screen depths for the estimates obtained from random media. Error can arise in the screen-depth estimates from random media data when only a single iteration is used for estimating phase because the change in focus depth caused mainly by refracting surfaces may not be adequately corrected. Furthermore, error in depth estimates can arise from incomplete convergence of the statistical estimates that result in broader cross-correlation peaks used to determine the screen depth.

Although improvement in representation of aberration achieved by using offset models is shown in Fig. 8, regions in the upper-right and lower-right panels have not been corrected by the offset. The lack of improvement in these regions is attributed mostly to 2 factors. One factor is that sources of aberration are located at different depths. These differences confound attempts to assign a single depth to the model. Some of the aberrators contain sources of aberration that are very close to the upper surface where the transducer is positioned. These features appear to be motionless in measurements from focuses at different locations. However, deep sources of aberration produce measurement features that shift as the location of the focus varies. Screens that model deep sources of aberrations are not able to accommodate the motionless features caused by shallow sources of aberration. Shallow sources of aberration can be seen in the video available at the web page given in [22]. The other factor is violation of the isoplanatic patch assumption. If the phase changes associated with shifting the focus location are not projective transformations of an offset phase screen, they cannot be corrected. This is the main reason for the uncorrected areas in

Fig. 8. The corruption that appears in Fig. 8 near the edges of the array occurs because the projection of a phase or time-shift screen onto the transducer array along rays from an offset focus subtend a rectangle that omits portions of the transducer array. These elements can be omitted from compensated transmissions, included in the transmissions without compensation, or populated with other factors. Compensations for these elements in this work result from the projective transformation of the phase screen that is tapered to reduce artifact that can arise because the projective transformation is performed in the spatial-frequency domain.

Fig. 10 shows that statistical models of aberration formed by phase and time-shift screens that are estimated at offset depths can produce effective compensation for focusing through complex aberration. However, if the sources of aberration are very deep, as in Aberrator 4064, then the effects of the aberration may not be accurately represented as phase variations along rays. Use of angular spectra may be more effective in these cases as a method for propagating fields from the transducer array to the surface of the model screen and vice versa. The statistical estimate of the screen should then be derived from measured fields that are more precisely backpropagated to the screen from the transducer array. Compensation coefficients for a given focal point can also be determined by more precise forward propagation from the focal point through the phase or time-shift screen and then on to the transducer array.

The b-scans of Fig. 11 further illustrate the benefits of using an offset model for aberration. Some improvement in b-scan imaging can be realized from statistical models of aberration that are not offset. This simpler approach may be justified in clinical scanners that do not require beam steering in lateral directions, because lateral beam steering benefits most from corrections that are associated with the screen depth. However, b-scans formed with compensation from models of aberration that are not offset will generally have contrast ratios that are not as good as the corresponding contrast ratios in b-scans formed with compensation from offset models because the side-lobes of focuses that employ the offset models are lower than the sidelobes of focuses that employ models that are not offset. This can be seen from the focus measurements in Fig. 10.

A region is generally said to be isoplanatic if the same aberration is experienced along the propagation paths from a single transducer element to all locations in the region. However, the exact size of the region depends on the stringency of the condition of equivalence for aberration along different paths. A practical way to define an isoplanatic region is to measure the quality of the focuses that are produced by a single set of compensation factors as the beam is steered to different locations. The isoplanatic region is then defined by the range of locations where the focus is of sufficient quality.

The notion of an isoplanatic region described is linked to aberration models that consist of a filter-bank at the transducer array. Regions are isoplanatic if the aberration in all signals that propagate between the region and the transducer array can be modeled by assigning a fixed (possibly different) filter to each transducer element. However, this interpretation of isoplanatic is not appropriate when considering more general models of aberration. A useful extension of the foregoing definition is to call a region isoplanatic when the aberration in all signals that propagate between the region and the transducer array can be accurately represented by a single set of model parameters for a given model. The model parameters can then be estimated from reflections that originate in an extended isoplanatic region and used to compensate focuses that are steered to locations in the same extended region. Thus, the significance of the traditional isoplanatic region is preserved by the extended definition.

An important feature of the offset-phase-screen and offset-time-shift models studied in this paper is that the extended isoplanatic regions associated with these models are larger than the isoplanatic regions associated with models that are not offset. This is shown by the experimental results, in which an improvement in focus quality is realized by use of the screen offset. Because the size of the extended isoplanatic region is determined by measurements of focus quality at different locations, models that improve focus quality inherently yield larger isoplanatic regions.

VI. Conclusion

Each set of factors for compensation of aberration in pulse-echo measurements can only be used to correct for aberration when focusing within a single isoplanatic patch. However, measurements of aberration from point reflectors that are not too far apart often show variations that can be modeled by phase or time-shift screens that are offset from the transducer array. These models yield compensation-factor variations that can correct focusing throughout a region larger than the isoplanatic patch.

The depth of screens that model aberration can be estimated using pairs of measurements from neighboring point reflectors. In these estimations, lateral shift of measurement features is interpreted as a parallax effect. Because point reflectors at known locations are not usually available in tissue, a statistical method is used to obtain the equivalent point-reflector responses. This method employs statistical estimates that are based on reflections from different patches of random media. The reflections that contribute to these estimates are localized by transmit and receive focusing.

The statistical method for developing a filter-bank model for aberration from random scattering that was presented in [15] has been extended to allow the filter-bank to be located at an offset depth rather than in the plane of the transducer array. The filter parameters in the offset model are computed by applying the method to scattering measurements that are backpropagated from the transducer array to the designated depth of the model. Use of an appropriate offset has the additional benefit of reducing measurement-to-measurement fluctuations. This results in better convergence of the statistical estimates.

Experimental results validate the methods for determining the depth of the filter-bank model and also the methods for determining the filter parameters for the model. In the validation, the performance of these methods was determined for aberration from a variety of tissue-mimicking aberrators. Focus quality was significantly improved by use of an offset in the aberration models. Similar improvement was also realized in the contrast resolution of b-scan images.

Acknowledgments

W. Badger and the University of Rochester Department of Imaging Sciences are thanked for donating time to visualize aberrators using magnetic resonance imaging. W. Pilkington is thanked for helpful discussions about the operation of the 2-D array system used for measurements.

This work was supported by NIH grant EB000280 and the University of Rochester Diagnostic Ultrasound research Laboratory Industrial Associates.

References

1. Flax SW, O'Donnell M. Phase-aberration correction using signals from point reflectors and diffuse scatterers: Basic principles. *IEEE Trans. Ultrason. Ferroelectr. Freq. Control* 1988;vol. 35(no. 6): 758–767. [PubMed: 18290213]

2. O'Donnell M, Flax SW. Phase-aberration correction using signals from point reflectors and diffuse scatterers: Measurements. *IEEE Trans. Ultrason. Ferroelectr. Freq. Control* 1988;vol. 35(no. 6): 768–774.
3. Nock L, Trahey GE, Smith SW. Phase aberration correction in medical ultrasound using speckle brightness as a quality factor. *J. Acoust. Soc. Am* 1989;vol. 85(no. 5):1819–1833. [PubMed: 2732378]
4. Ng GC, Freiburger PD, Walker WF, Trahey GE. A speckle target adaptive imaging technique in the presence of distributed aberrations. *IEEE Trans. Ultrason. Ferroelectr. Freq. Control* 1997;vol. 44(no. 1):140–151. [PubMed: 18244111]
5. Krishnan S, Rigby KW, O'Donnell M. Improved estimation of phase aberration profiles. *IEEE Trans. Ultrason. Ferroelectr. Freq. Control* 1997;vol. 44(no. 3):701–713.
6. Li Y. Phase aberration correction using near-field signal redundancy. I. Principles [ultrasound medical imaging]. *IEEE Trans. Ultrason. Ferroelectr. Freq. Control* 1997;vol. 44(no. 2):355–371. [PubMed: 18244133]
7. Li Y, Robinson D, Carpenter D. Phase aberration correction using near-field signal redundancy—Part II: Experimental results. *IEEE Trans. Ultrason. Ferroelectr. Freq. Control* 1997;vol. 44(no. 2): 372–379. [PubMed: 18244134]
8. Liu DL, Waag RC. Correction of ultrasonic wavefront distortion using backpropagation and a reference waveform method for time-shift compensation. *J. Acoust. Soc. Am* 1994;vol. 96(no. 2): 649–660. [PubMed: 7930065]
9. Fried DL. Statistics of a geometric representation of wavefront distortion. *J. Opt. Soc. Am* 1965;vol. 55:1427–1435.
10. Benedict R Jr, Breckinridge JB, Fried DL. Special issue: Atmospheric compensation technology. *J. Opt. Soc. Am. A* 1994;vol. 11(no. 1):263–831.
11. Dowling DR, Jackson DR. Narrow-band performance of phase-conjugate arrays in dynamic random media. *J. Acoust. Soc. Am* 1992;vol. 91(no. 6):3257–3277.
12. Fink M. Time-reversal of ultrasonic fields-Part I: Basic principles. *IEEE Trans. Ultrason. Ferroelectr. Freq. Control* 1992;vol. 39(no. 5):555–566. [PubMed: 18267667]
13. Roux P, Derode A, Peyre A, Fink M. Acoustical imaging through a multiple-scattering medium using a time-reversal mirror. *J. Acoust. Soc. Am* 2000;vol. 107:7–12.
14. Pilkington, WC. Ph.D. thesis. Rochester, NY: University of Rochester; 2005. Isoplanatic patch size for aberration correction in ultrasonic imaging.
15. Waag RC, Astheimer JP. Statistical estimation of ultrasonic propagation path parameters for aberration correction. *IEEE Trans. Ultrason. Ferroelectr. Freq. Control* 2005;vol. 52(no. 5):851–869. [PubMed: 16048187]
16. Waag RC, Phillips DB, Lacefield JC, Draeger CG, Lin F, Tabei M. A two-dimensional array system for studies of ultrasonic imaging with aberration correction. *J. Acoust. Soc. Am* 1999;vol. 106:2134.
17. Lacefield, J.; Phillips, D.; Waag, R. Calibration of a two-dimensional array system for ultrasonic aberration correction; 138th Meeting of the Acoustical Society of America; 1999. p. 2136
18. Astheimer J, Pilkington W, Waag R. Reduction of variance in spectral estimates for correction of ultrasonic aberration. *IEEE Trans. Ultrason. Ferroelectr. Freq. Control* 2006;vol. 53(no. 1):79–89. [PubMed: 16471434]
19. Måsøy S-E, Varslot T, Angelsen B. Iteration of transmit-beam aberration correction in medical ultrasound imaging. *J. Acoust. Soc. Am* 2005;vol. 117(no. 1):450–461.
20. Liu DLD, Waag RC. Estimation and correction of ultrasonic wavefront distortion using pulse-echo data received in a two-dimensional aperture. *IEEE Trans. Ultrason. Ferroelectr. Freq. Control* 1998;vol. 45(no. 2):473–490. [PubMed: 18244198]
21. Liu D-L, Waag RC. Time-shift compensation of ultrasonic pulse focus degradation using least-mean-square error estimates of arrival time. *J. Acoust. Soc. Am* 1994;vol. 95(no. 1):542–555. [PubMed: 8120265]
22. Tillett, JC. Offset Phase Screen Model Videos. 2009. [Online]. Available: <http://www.ece.rochester.edu/projects/ultrasoundres/OffsetScreen>

Biographies

Jason C. Tillett received a B.S. degree in physics and astronomy from the University of Rochester in 1986 and a Ph.D. degree in physics from the University of Delaware in 1992. After completing his Ph.D., he founded a small internet service provider that he left to accept a fellowship at the Rochester Institute of Technology. Since 2004, he has worked as a Research Associate in the Ultrasound Research Laboratory at the University of Rochester. His current activities and interests include experimental ultrasound imaging with aberration correction and large-scale calculations of wave propagation using high-performance

computing. He is a member of the Acoustical Society of America and the American Institute for Ultrasound in Medicine.

Jeffrey P. Astheimer received a B.A. degree in mathematics in 1975, an M.A. degree in mathematics in 1977, and a Ph.D. degree in mathematics in 1982, all from the University of Rochester. After completing his Ph.D., he joined the faculty of Colgate University in 1984, but left in 1985 to co-found the Adaptable Laboratory Software company which developed the Asyst software system. Dr. Astheimer spent 19 years in commercial scientific software development, but has also retained a long-term interest in the mathematics of wave propagation, especially as it relates to applications in medical ultrasound.

Robert C. Waag received his B.E.E., M.S., and Ph.D. degrees from Cornell University in 1961, 1963, and 1965, respectively. After completing his Ph.D. studies, he became a member of the technical staff at Sandia Laboratories, Albuquerque, NM, and then served as an officer in the United States Air Force from 1966 to 1969 at the Rome Air Development Center, Griffiss Air Force Base, NY. In 1969, he joined the faculty of the University of Rochester where he is now Arthur Gold Yates Professor in the Department of Electrical Engineering, School of Engineering and Applied Science, and also holds an appointment in the Department of Radiology, School of Medicine and Dentistry. Prof. Waag's recent research has treated ultrasonic scattering, propagation, and imaging in medical applications. In 1992, he received the Joseph H. Holmes Pioneer Award from the American Institute of

Ultrasound in Medicine. He is a life fellow of the Institute of Electrical and Electronics Engineers and a fellow of the Acoustical Society of America and the American Institute of Ultrasound in Medicine

Fig. 1.

Experimental configuration. Two focus positions and a hydrophone used for measurements and a point reflector are shown. Also shown is the position of an offset screen that produces varying phase in the transducer as the focus position shifts.

Fig. 2.

Phase estimation from random scattering. The configuration of 2 experiments is shown. In one configuration, depicted in the left expansion of the region of interest (ROI), the phase-screen depth is estimated by performing 2 phase-estimation experiments centered on offset volumes. In another configuration, depicted in the right expansion of the ROI, a set of approximately coplanar focuses is used to form a point response for statistical estimation of phase.

Fig. 3. Projective transformation. The offset phase screen appears spatially shifted and dilated in the transducer aperture.

Fig. 4. Steps for iterative phase calculation from random-medium scattering by using the offset-screen model.

Fig. 5. Magnetic resonance images. Central cross sections of the studied aberrators are shown. The dimensions of the areas are approximately 35×165 mm.

Fig. 6.

Aberrator-dependent phase-screen depths. Phase cross correlations (Phase) and time-shift cross correlations (TSE) computed from point-reflector echoes produced similar phase-screen depths. Also shown for comparison is the phase-screen depth estimate from random-scattering measurements (RM). The error bars for point-reflector results depict the mean and standard deviation of the screen-depth estimates obtained from 28 pairs of reflector locations.

Fig. 7. Phase-screen depth versus temporal frequency from point-reflector measurements. No correlation between temporal frequency and phase-screen depth is apparent. This is consistent with results shown in Fig. 6.

Fig. 8.

Statistics of time shifts for Aberrator 4064. The upper-left panel shows the average of time shifts computed using echos received from a point-reflector placed at each position in the set of focuses shown in the right expansion of the region of interest depicted in Fig. 2. The upper-right panel shows the standard deviation of the set of time-shift maps at each element location for the set of maps used to form the average map in the upper-left panel. The lower panels show the same data as the upper panels except that each time-shift map has been depth-corrected using the measured phase-screen depth.

Fig. 9.

Focus effective-width measurements that show focus improvement from a spatial shift of a transmit compensation filter. The measurements used Aberrator 4064. A = Uncompensated, B = Steered and compensated with the center-focus phase, C = Steered and compensated with the shifted center-focus phase, D = Compensated with the center-focus phase.

Fig. 10.

Hydrophone measurements of a focus through aberrators with differing distributions of aberration. A = Uncompensated, B = Compensated with statistical estimate, C = Compensated with statistical estimate (offset-screen model), D = Compensated with center-focus phase, E = Water path.

Fig. 11. Comparison of b-scans performed with (b) and without (a) offsets using the filter-bank model. The contrast ratios are the difference in decibels between the mean intensity in the scatterer-free region of interest (vertically centered circle in each image) and the background region of interest (upper and lower circles in each image).

TABLE I

Physical Properties¹ of Studied Aberrators

Aberrator	Background			Aberrating Inclusions		
	<i>c</i> (m/s)	ρ (g/mL)	α (dB/(cm MHz))	<i>c</i> (m/s)	ρ (g/mL)	α (dB/(cm MHz))
4491	1451	0.94	0.77	1496	0.91	0.52
6277	1473	0.96	0.30	1485	0.98	0.40
6289	1450	0.92	0.43	1473	0.97	0.43
4064	1518	0.94	0.55	1412	0.80	0.18

¹ *c* = sound speed; ρ = density; α = attenuation; *T* = temperature.

TABLE II

Aberrator Strength is Based on Arrival-Time Fluctuations (ATF).¹

Aberrator	ATF (ns)	Strength	Model
4491	73	Strong	Distributed shallow screen
6277	56	Medium	Distributed shallow screen
6289	79	Strong	Distributed deep screen
4064	63	Medium	Planar deep screen

¹The aberrator model description is based on phase-screen depth measurements and *a priori* information. For example, Aberrator 4064 was constructed to contain pseudorandomly-positioned spherical depressions on one surface. The depressions ranged from 3.0 to 9.5 mm in diameter and 0.4 to 4.0 mm depth, and were filled with mineral oil. The aberrator was oriented with the dimpled surface facing away from the transducer surface to create a planar phase screen positioned on the far side of the aberrator.

TABLE IIIStatistics¹ That Quantify Agreement Between the Offset-Screen Phase and the Experimental Phase

Aberrator	σ_1 (rad)	σ_2 (rad)	Intrinsic screen depth (mm)	Apparent screen depth (mm)
6277	0.238	0.200	8.5	9.5
4491	0.538	0.443	8.5	11.5
6289	0.940	0.865	17	18.0
4064	0.959	0.744	30	31.0

¹ σ_1 = standard deviation for the difference between the unshifted and the experimental phase; σ_2 = standard deviation for the difference between the shifted and the experimental phase. Apparent screen depth includes the flying distance, i.e., the small gap between the aberrator and the transducer.

TABLE IVThe Offset-Screen Model Improves Time-Shift Estimates for Deep Phase Screens¹

Aberrator	ATF increase (ns)	Standard deviation decrease (ns)	Apparent screen depth (mm)
6277	-0.1	-0.5	9.5
4491	0.1	1.0	11.5
6289	2.3	6.1	18.0
4064	4.4	10.6	31.0

¹ ATF = arrival-time fluctuations. Apparent screen depth includes the flying distance, i.e., the small gap between the aberrator and the transducer.