Whitepaper

Retrospective Transmit Beamformation

ACUSON SC2000 Volume Imaging Ultrasound System

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Abstract

The acquisition rates required to achieve real-time volume rates in full-volume ultrasound imaging are enormously greater than those typically used in real-time 2D imaging. One consequence of high acquisition rates is a susceptibility to an imaging artifact known as a “beam group” artifact which is caused by the use of static transmit focusing at high acquisition rates. In order to achieve acceptable image quality at real-time volume rates, transmit focusing must be made dynamic. Retrospective Transmit Beamformation (RTBF) is a transmit focusing technology that achieves dynamic focusing by performing the transmit focusing operation retrospectively. RTBF is a central component of Coherent Volume Formation™, the image formation technology that has been implemented on the ACUSON SC2000™ volume imaging system specifically to enable real-time volumetric imaging.

Introduction

By far the greatest challenge faced in the realization of real-time volumetric ultrasound imaging lies in the achievement of real-time volume rates with comparable image quality to what users have become accustomed. The reason this is such a challenge lies in the fact that the basic image acquisition paradigm that has been in place for decades to support real-time 2D imaging simply does not support real-time volumetric imaging. A very different image acquisition paradigm must be used.

There are two basic shortcomings inherent in the 2D acquisition paradigm that render it incapable of supporting real-time volumetric imaging. First, the 2D paradigm is a serial, line-by-line acquisition paradigm that is simply too slow for use in volumetric imaging. Traditionally a 2D ultrasound image is composed of a set of perhaps 100 lines, and the imaging engine acquires image data along each of these lines, one after another, until a full frame has been scanned. The corresponding volumetric image would be composed of 100 squared or 10,000 lines, so the time to scan a full volume would be 100 times greater than the time necessary to scan a 2D frame. In order to achieve real-time volume rates, the method must move from a serial acquisition scheme to a highly parallel scheme in which multiple receive beams are simultaneously formed in parallel. As opposed to a serial or “line-by-line” acquisition design, this is a parallel or “subvolume-by-subvolume” design.

The second inherent shortcoming in the 2D acquisition model lies in the type of focusing that is used during the transmit cycle. There are two very different forms of focusing that are used in ultrasound imaging: static and dynamic. Static focusing is used during the transmit cycle. Dynamic focusing is used during the receive cycle. (These two forms of focusing will be described in detail later). The problem lies in the use of static focusing during the transmit cycle. Where static transmit focusing yields sufficient image quality in the low acquisition rate, line-by-line 2D paradigm, it does not yield adequate image quality in the high acquisition rate, subvolume-by-subvolume volumetric paradigm. In order to rectify this image quality issue, transmit focusing must be made dynamic. Retrospective Transmit Beamformation (RTBF) is a focusing technology that enables dynamic transmit focusing at the very high acquisition rates necessary for real-time volumetric imaging. As such, RTBF is an enabling technology for real-time volumetric imaging.

Static Versus Dynamic Beamformation

In order to underscore the inherent shortcomings in static transmit beamformation it is necessary to review the difference between static and dynamic beamformation. Consider first conventional static transmit beamformation. In order to generate a beam of ultrasound, a set of very short-duration (i.e., broadband), high-voltage electrical signals are generated and sent to the various elements of the transducer. If these signal bursts were all to occur simultaneously, the resultant acoustic field would be planar (i.e., unfocused), and unsteered. If, on the other hand, these pulses are delayed relative to one another, then the resultant beam may be steered and focused. The application of a delay profile that includes curvature, in particular, gives rise to an acoustic field with curvature, and this curvature in turn causes focusing. **Figure 1** shows a series of snapshots of such a transmitted ultrasound field at several instances in time. The thin, curved sheet of ultrasound energy sweeps down the beam axis, converging as it travels towards the focal depth, and diverging once it has surpassed the focal depth. All scattering objects that lie within the "swept path" of this transmitted beam, shown schematically in **Figure 2**, scatter sound, some of which is scattered back towards the transducer. Note that the swept path has the characteristic hourglass shape that is normally associated with a focused beam; a familiar example being a beam of light that has traveled through a lens.

Note that the curvature of the delay profile determines the curvature of the acoustic field, which in turn determines the focal depth. A sharply curved delay profile gives rise to a sharply curved wavefront, which focuses at a shallow depth. A flatter delay profile, on the other hand, gives rise to a more gently curved wavefront, which focuses at a larger depth.

Immediately after the transmitted beam is launched, the transducer elements are disconnected from the transmit beamformer and connected to the receive beamformer. The elements then become receivers and pick up the

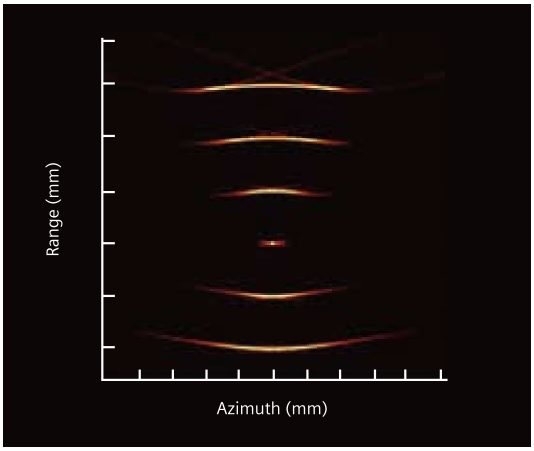


Figure 1.

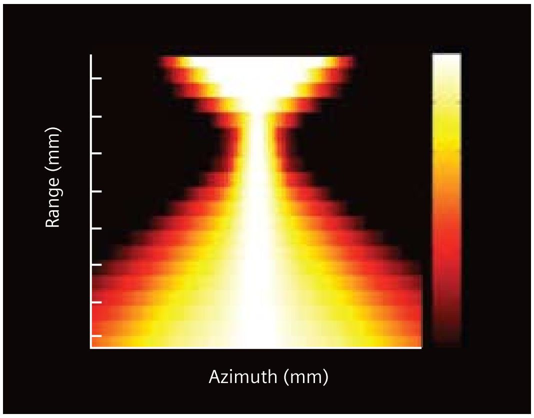


Figure 2.

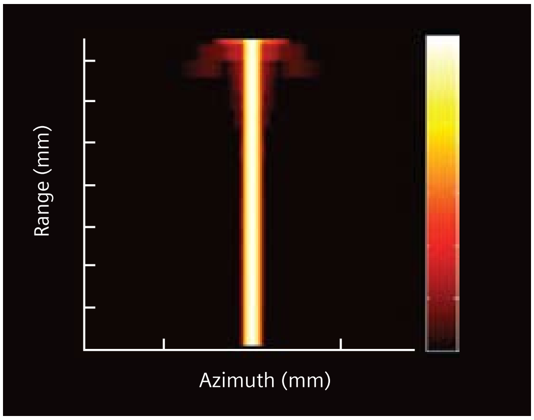


Figure 3.

backscattered echoes from all the scattering objects in the transmit beam's swept path. These received signals are then sent to the receive beamformer, which performs a dynamic delay-and-sum operation: dynamic receive focusing.

With dynamic focusing, the focal delay profile evolves with time, and therefore with range. Specifically, early in the receive cycle, when the receive beamformer is processing the echoes from shallow objects, the focusing delay profile is sharply curved, thereby focusing at a shallow depth. Later, when the echoes from deeper objects are being processed, the delay profile is flatter and therefore focuses at a larger depth. In stark contrast to the transmit beam, which is only in true focus at a single depth, the receive beamformer is in perfect focus at all depths. The corresponding beam pattern is therefore the thin pencil beam shown in **Figure 3**.

From this explanation it can be easily appreciated why receive beamformation is typically dynamic, and transmit beamformation is typically static. At any particular point in time during the receive cycle, the receive beamformer is processing the echoes that originate at a known depth, and so the delay profile that focuses at that depth is used. As echoes are returning from multiple depths within the image, instead of using a single, static delay profile, a dynamically evolving sequence of profiles can be used. Transmit, on the other hand, is a single, discrete event. There can only be a single delay profile associated with a particular transmit event. Once the transmit field is launched, it has the curvature associated with the delay profile and so will focus at the associated depth. In short, as receive focusing delays are applied after propagation occurs, the receive beamformation may be dynamic. In the case of transmit, on the other hand, the focusing delays are applied prior to the occurrence of any propagation so the beamformation must (apparently) be static.

Following this perspective, it is not obvious how transmit beamformation can be made dynamic. Can the curvature of a waveform be modified during propagation? Before going into a description of how this can be done via retrospective focusing, it is necessary to review the artifacts that are encountered if such an effort is not made.

Volumetric Imaging and the Beam Group Artifacts Inherent in Static Transmit Focusing

The artifacts associated with static transmit focusing, known as "beam group" artifacts, traditionally have not been a issue as the presence of the artifact is highly dependent upon acquisition rate. In real-time 2D imaging, acquisition rates are low enough that the artifacts are negligible, or at least acceptable. In real-time volumetric imaging, on the other hand, the acquisition rates are enormously greater than those in 2D, and this in turn intensifies the beam group artifacts.

The benefit of dynamic transmit focusing is acquisition-rate dependent and relates to the number of receive beams that are simultaneously formed following any particular transmit event. In real-time 2D imaging, high acquisition rates are not necessary, so typically a very small number of simultaneous receive beams are formed (usually one or two) following each transmit event. This translates to a serial or line-by-line acquisition scenario. In real-time 3D imaging, on the other hand, a substantial number of receive beams are formed in parallel following each transmit event. In this way, a subvolume is imaged during each transmit event, instead of just a single line.

Consider the 2D imaging case where a single receive beam is used. The transmit hourglass beam is steered along a scan line, and the receive pencil beam is formed along the same line. The net imaging performance is contributed to by both the transmit and the receive beam, and is determined by the product of the transmit hourglass beam profile and the receive pencil beam profile. As these two beams lie along the same axis (they are co-axial), the resultant product is (1) highly symmetric, and (2) laterally invariant (i.e., has the same form from line to line). These characteristics of the net beam profile turn out to be the key to artifact-free imaging.

Conversely in real-time full volume imaging, large numbers of receive beams must be simultaneously formed following any particular transmit event in order to achieve real-time volume rates. After the transmit beam is launched, this set of receive pencil shaped beams, stacked side-by-side, are formed. The central receive beam in the group typically lies along the same axis as the transmit beam, and therefore exhibits the same symmetry and lateral invariance as in the artifact-free single beam case. Receive beams toward the outer edges of the group, however, lie off to one side of the transmit beam. As a result, the disparity between the axes of the transmit and receive beams becomes substantial, and, as a consequence, both the symmetry and lateral invariance of the round-trip beam pattern are degraded. An example of the resultant beam-group artifact is shown in **Figure 4** in a cardiac application. While the diagnostic and workflow benefits of real-time, full-volume imaging are enormous, such severe imaging artifacts greatly compromise those benefits.

Retrospective Transmit Beamformation

As previously noted, the root of the problem lies in the fact that there are multiple receive beams associated with any particular transmit event, and the resulting disparity between the axis of the transmit beam and the axes of at least some of the receive beams. This disparity in turn causes beam group artifacts. In order to rectify this problem, the transmit beam must be focused simultaneously along each of the many receive beams in the RX beam group. In other words, transmit focusing must be not only dynamic, but "repeatedly dynamic". RTBF is a technology that is capable of performing precisely this type of focusing, and achieves this result by performing the focusing operation retrospectively (i.e., following propagation). Recall that when the focusing operation is performed after propagation, it can be made dynamic.

To see how transmit focusing can be made retrospective, and therefore dynamic, consider the definition of focusing.

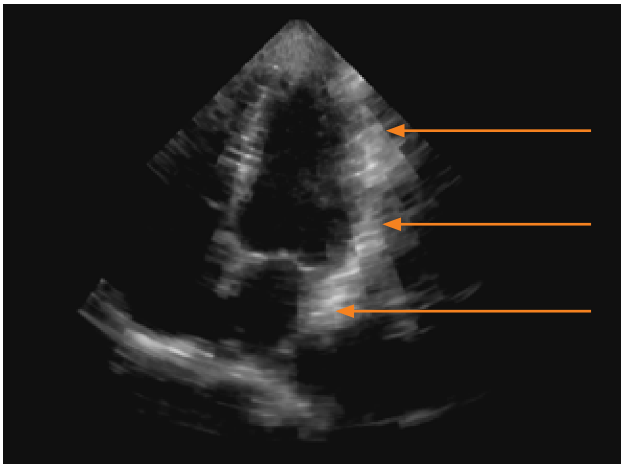


Figure 4.

At focus, the ultrasonic energy is incident to the focal point from a variety of different directions. Every other point in the field is, by contrast, insonified from a single direction. **Figure 5** shows the statically focused transmit field from **Figure 1**, but with arrows to indicate the local insonification directions. Note that each of the wavefronts shown in **Figure 5** contains the same set of "directions". At the focal depth these "directions" are all concentrated at a single point, and at other depths they are distributed broadly across the width of the wavefront. Such "direction components" are commonly referred to as either angular spectral components or lateral spatial frequency components.

The diversity of incident directions at any particular point in the field is a key determinant of image quality. The image at the transmit focal depth is associated with high angular diversity (in angular spectral terms, is laterally broadband) and high image quality. The image at other depths is associated with low angular diversity (is laterally narrowband) and lower image quality.

Now consider what happens during a typical ultrasound scan, where a set of such focused transmit fields is directed, transmit event by transmit event, along a sequence of steering angles, such as the set shown in **Figure 6**. Points in the tissue that are far from the focal depth, for example very shallow points, are insonified a number of times during subsequent transmit events (see **Figure 7**). This results from the broad transmit field at shallow depths,

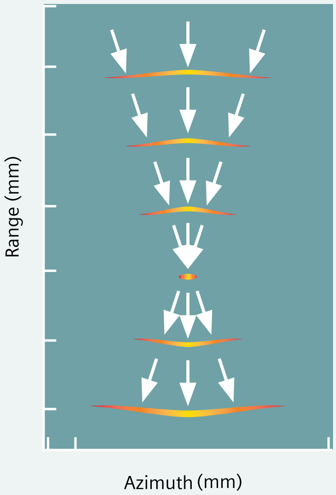


Figure 5.

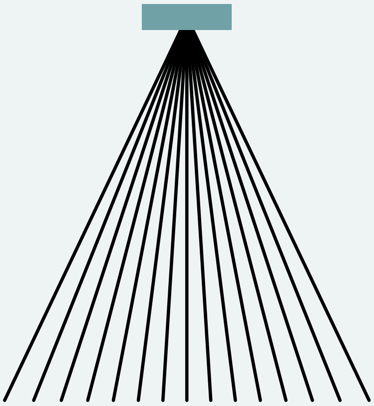


Figure 6.

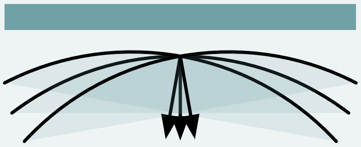


Figure 7.

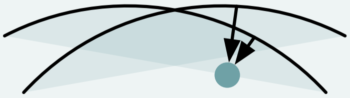


Figure 8.

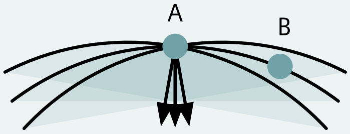


Figure 9.

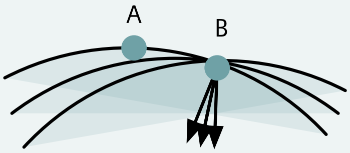
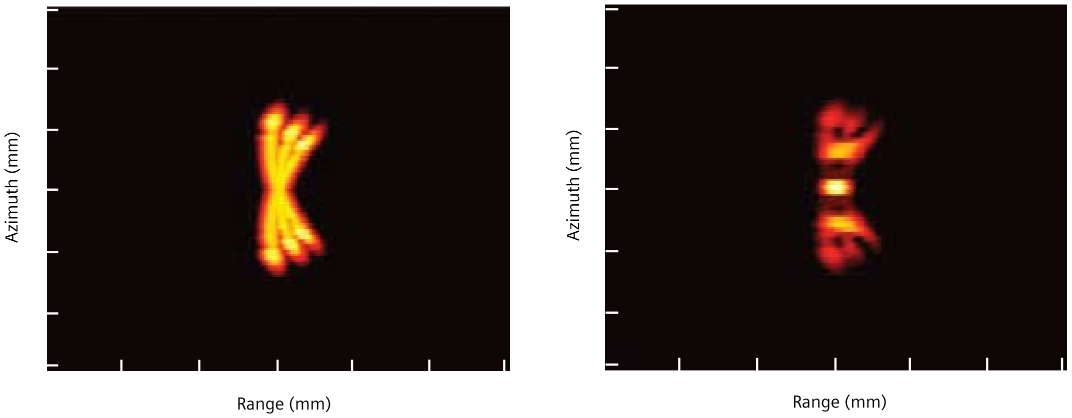


Figure 10.

with subsequent transmit fields generally overlapping. During any particular transmit event, the field is incident from a single direction, but during subsequent transmit events, the same point is insonified multiple times, each time from a different direction (see **Figure 7**). If an image is formed during each of these multiple insonifying events, then each individual image is laterally narrowband, as the insonifying field was incident from only a single direction. The collection of these laterally narrowband images contain all the angular diversity normally associated only with the focal depth. As such, the collection of images contains all the information necessary to synthesize a single image that is laterally broadband at all depths.

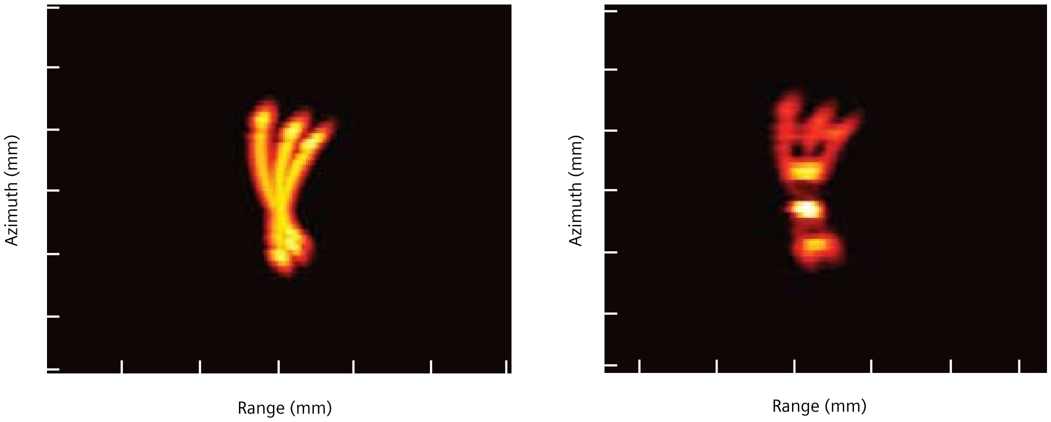
In order for this synthesis process to successfully result in good focusing, the phases of the contributing beams must be aligned. Because the transmit field is steered from firing to firing, it generally takes different amounts of time for the incident field to reach any particular imaging point (see **Figure 8**). Consider, for example, the three transmit fields shown schematically in **Figure 9**. The arrival time of the incident field at point A is the same for each transmit event. As such, one may simply add the resultant images, with no applied delay, and synthesize focusing of the transmit field at point "A". For point B", on the other hand, the arrival times of the three incident fields differ. In order to synthesize focusing at point B, one must apply delay to the image data prior to summing. As pulse-echo imaging time is mapped to range, the "application of delay" to such image data is achieved simply by use of the image data from different depths. To synthesize focusing at point B, then, one must sum component image data from different depths in each component frame; the depth of each contributor being proportional to the insonification time delay. **Figure 10** is an example of such a range adjustment. Adding the range-adjusted image data results in focusing of the field at point B.



A. Individual components

B. Focused

Figure 11.



A. Individual components

B. Focused

Figure 12.

Figures 11 and 12 are simulations demonstrating focusing of the transmit field by use of range adjustment and summing. In each case, in (a) a set of three transmit wavefronts and in (b) the delayed and summed resultant; the effective transmit field. **Figure 11** is a simulation of the example shown schematically in **Figure 9**, where the desired focal point is unsteered. **Figure 12**, on the other hand, is a simulation of the steered example shown schematically in **Figure 10**.

This retrospective focusing technique, along with several other phase-sensitive or *coherent* imageformation technologies collectively referred to as Coherent Volume Formation (see the whitepaper entitled "High Information Rate Volumetric Ultrasound Imaging", by Kutay Ustuner), has been implemented on the ACUSON SC2000 system. The ACUSON SC2000 system was designed specifically for real-time volumetric imaging. Coherent Volume Formation, with RTBF as a central feature, represents the enabling technology.

Conclusions

In order to achieve acceptable image quality at the high acquisition rates necessary for real-time volumetric imaging, the static transmit focusing method in use for decades must be replaced with dynamic focusing. Retrospective Transmit Beamformation (RTBF) is a dynamic transmit focusing technology that achieves dynamic focusing by performing the focusing operation retrospectively. Each point in the volume is imaged multiple times, each time with the transmitted acoustic field incident from a different direction. The combination of these multiple images (after compensating for the arrival time of the incident field) results in the synthesis of a transmit beam that is in focus everywhere in the volume. Such dynamic focusing greatly reduces transmit focusing artifacts while retaining high acquisition rates necessary for real-time volumetric imaging.

Standalone clinical images may have been cropped to better visualize pathology.

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