

# ULTRASOUND STORAGE CORRELATOR ARRAYS FOR REAL-TIME BLOOD FLOW VELOCITY VECTOR IMAGING

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## ABSTRACT

Conventional speckle tracking method can be used for blood flow velocity vector imaging. However, it requires a large amount of computations. In this paper, storage correlator array is used to perform the correlations for blood flow velocity vector imaging at a high frame rate. In the method, sliding correlations are used for speckle tracking and matching. Previous speckle patterns are stored as reference signals in the storage correlator arrays, waiting for tracking current speckle patterns. The reference signals stored can be easily programmed, rewritten, or erased at any time. A blood flow velocity vector image can be obtained from peaks of correlations between the previous and the current speckle patterns.

## INTRODUCTION

Storage correlator array<sup>1-4</sup> is a key component in high frame rate<sup>5-6</sup> blood flow velocity vector imaging due to their short processing time. They can be used effectively as a programmable matched filters to improve the signal-to-noise ratio (SNR) of signals. The programmable feature of storage correlator arrays allows speckle patterns stored to be updated for each frame of constructed radio-frequency (RF) image (an RF ultrasound image is one before an envelope detection). Real-time tracking and matching of previous and current speckle patterns make high speed blood flow velocity vector imaging practical. The high-speed processing also increases the maximum measurable velocities.

Conventional speckle tracking techniques<sup>7-9</sup> estimate the motion of objects based on speckle pattern matching and correlation algorithms. Velocity vector images are obtained by comparing the speckle pattern in a small kernel region in the current image to each

possible match in a larger surrounding search region in the previous one. The best match indicates the most likely location to which the speckle pattern has moved. The displacement of the best match and the time between the acquisition of the kernel and search regions are used to compute blood flow velocity vectors, thereby overcoming the limitations of conventional Doppler-based velocity estimators: angle dependence and aliasing. However, the conventional speckle tracking method is limited by several factors. One of them is that it takes a long time to calculate the correlation between the kernel and search regions and to search for the best matching speckle pattern. The long searching time may reduce the correlation between the kernels and the possible matches in search regions producing fault results.

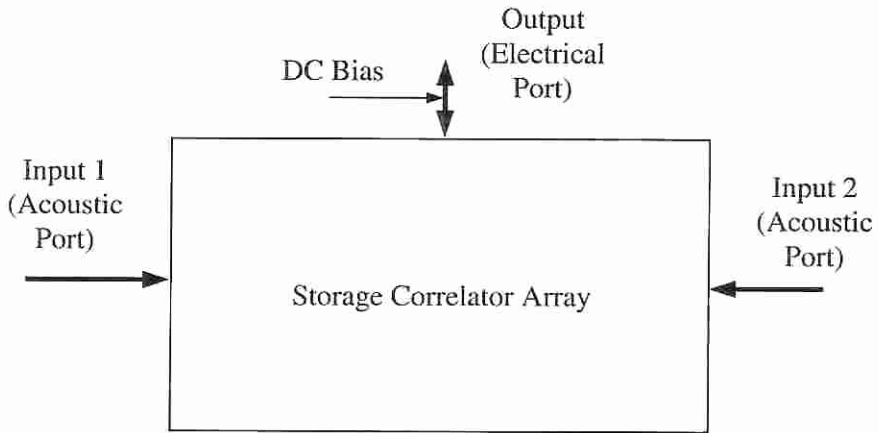
To overcome the problem, in this paper, storage correlator arrays are used to perform the integrations of correlations for real-time speckle tracking. The operations of storage correlator arrays can be categorized into two models depending on how the integration is carried out, i.e., time-domain<sup>10-12</sup> and space-domain processing models<sup>13</sup>. In time-domain processing, integrations of correlated signals accumulate stored charges over time and the time bandwidth product is determined by the product of the transducer bandwidth and the storage time of the storage correlation arrays. Because storage correlation arrays have a long storage time, the processing gain of the signal is increased greatly. In space-domain processing, signal integration is carried out across a one- or two-dimensional space. The time bandwidth product of the signals is determined by the transducer bandwidth and the propagation time of ultrasound waves across a diode array.

Although the time bandwidth product of space-domain processing model is smaller than that of the time-domain processing, the space-domain model is better suited for real-time speckle tracking and matching. In the processing, a RF image constructed from a previous data acquisition is stored in a storage correlator array as a reference. Then, cross-correlations between the previously stored image and the multiple kernels obtained from the second RF image are processed with the storage correlator array in parallel. The outputs of the storage correlator array produce correlation peaks that indicate the location of possible matches. Velocity vector images of motions can thus be obtained. In addition, storage correlator arrays have a very large storage capacity and images stored can be easily overwritten or erased. The size of correlator arrays is small (usually about tens of millimeters in signal length and a few micrometers for each storage element).

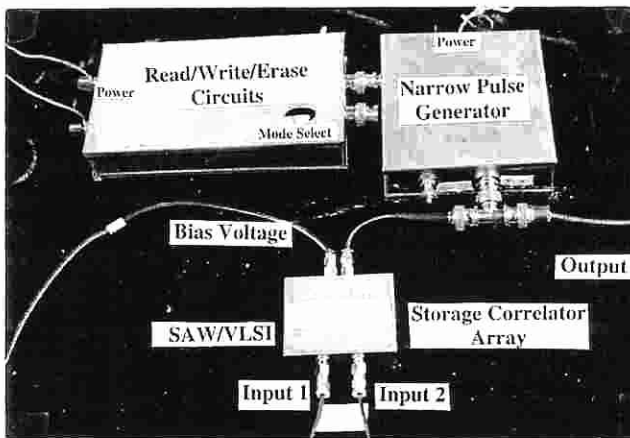
## STORAGE CORRELATOR ARRAYS

A storage correlator array is a device that can store a snapshot of the waveform of a surface acoustic wave (SAW) while the wave propagates from one finger transducer to another<sup>11</sup>. A simple storage correlator array has three ports (two acoustical and one electrical) (Fig. 1). Storage elements are usually a diode array. The storage principle is based on a nonlinear interaction between the waves and the diodes. Two systems consisting of such devices are shown in Figs. 2 and 3, respectively. Internal structure of a storage correlator array is shown in Fig. 4.

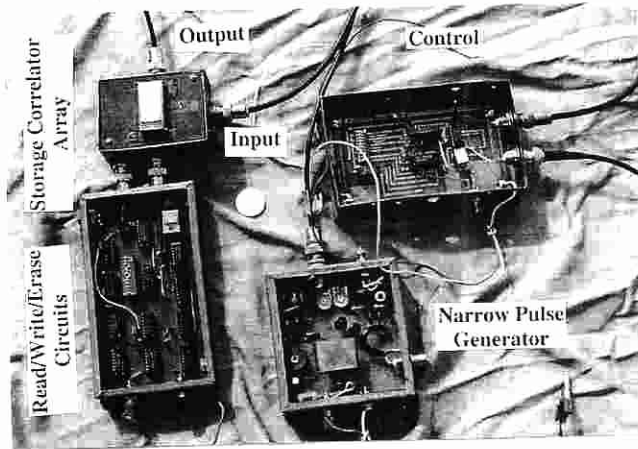
The device shown in Fig. 2 has a center frequency of 76 MHz (typical frequency is between 10MHz to a few GHz) with an interaction distance (where waveforms can be stored) of 20 mm, a diode size of  $4\ \mu\text{m} \times 4\ \mu\text{m}$ , and an inter-diode distance of  $4\ \mu\text{m}$ . The speed of sound of this device is close to 4000 m/s. The diode array is situated above an ultrasound piezoelectric delay line with 3-phase unidirectional transducers.



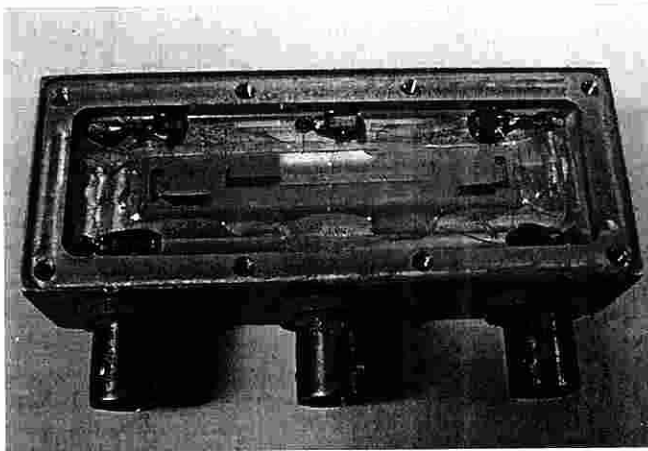
**Figure 1.** Simplified block diagram of a storage correlator array.



**Figure 2.** A subsystem consisting of a SAW/VLSI storage correlator array.



**Figure 3.** A subsystem with a high efficiency GaAs storage correlator array.



**Figure 4.** Internal structure of a storage correlator array.

To write a waveform into the diode array (write-in process), a short pulse of a width of a few nanoseconds can be applied through the electrical port. After storage, a signal that is proportional to the correlation or convolution between the stored waveform and the waveform input from one of the two acoustic ports can be read out from the electrical port (readout process). A DC bias of about 10V can be applied to increase the amplitude of output signals. The waveform storage time of the diodes is from hundreds of milliseconds to a few seconds and is a function of the DC bias voltage.

An experiment result of the autocorrelation with the storage correlator array in Fig. 2 is shown in Fig. 5. The waveform in the first row represents a signal that was stored in the diode array. The signal in the second row represents an autocorrelation of the stored signal.

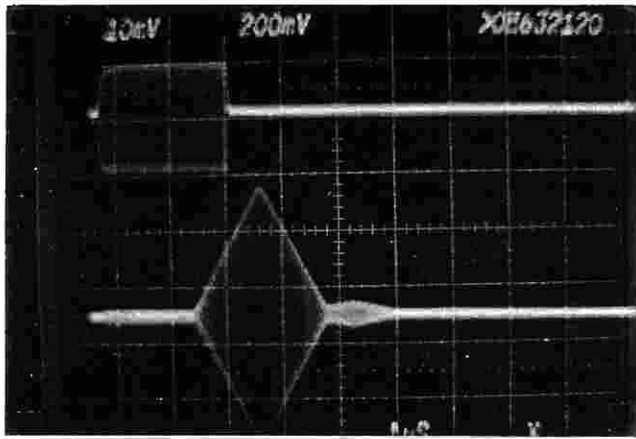


Figure 5. Autocorrelation of a tone burst with the storage correlator array shown in Fig. 2.

A simulation of the autocorrelation of a 31-chip pseudorandom (PN) code is shown in Fig. 6 and its corresponding experiment using the storage correlator array in Fig. 2 is shown in Fig. 7.

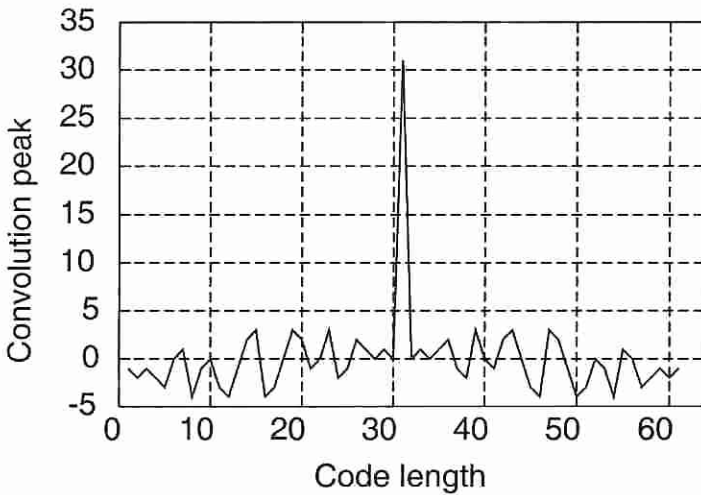


Figure 6. Simulation of autocorrelation of a 31-chip PN code.

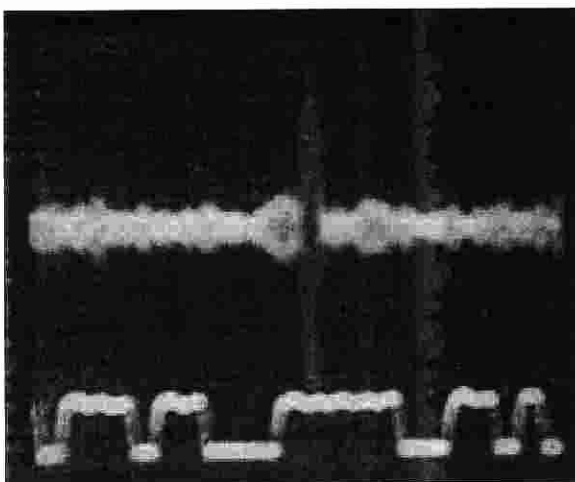


Figure 7. Experiment of autocorrelation of the same PN code as in Fig. 6.

## VELOCITY VECTOR ESTIMATIONS

Speckle tracking techniques<sup>7-9,12</sup> can be used to obtain a blood flow velocity vector by comparing the speckle pattern in a small kernel region of the second image to each possible match in a larger surrounding search area of the first. The best match indicates the most likely location to which the speckle pattern, and thus the target, has moved. The location of the best match and the time between the acquisitions of the two images are used to estimate the velocity vector of the kernel.

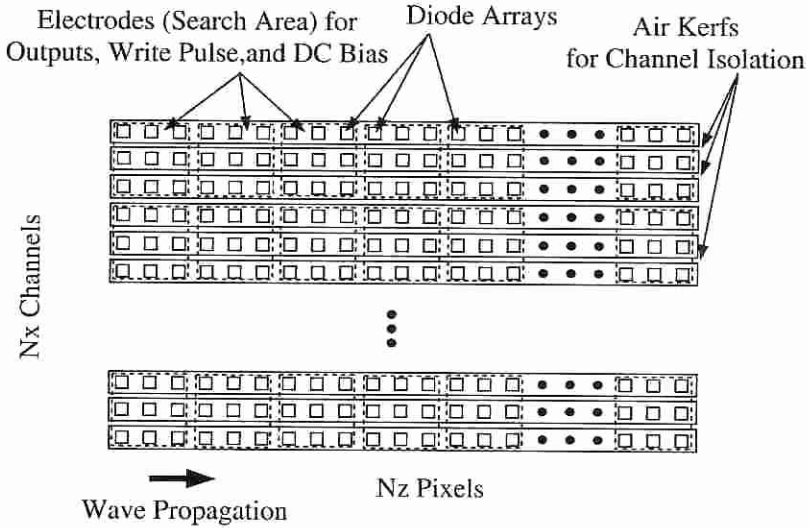
To implement the speckle tracking techniques in practice, there are two major problems. The first is pattern decorrelation due to low frame rate of ultrasound images, and the second is a large amount of computation required.

Recently, a high frame rate imaging method that could be used to construct images at a frame rate up to 3750 frames or volumes/second for biological soft tissues at a depth of about 200 mm was developed<sup>5,6</sup>. This may address the first problem because the time between two consecutive frames is only about 267  $\mu$ s. During this time, a fast blood stream at 5 m/s moves about 1.3 mm. Therefore, speckle decorrelation will not be a problem for frequencies used in medical diagnostic ultrasound (1 to 10 MHz). In the following, an approach is proposed for solving the second problem using storage correlator arrays.

Assuming two consecutive 2D RF images of size  $N_x \times N_z$  are constructed with the high frame rate imaging method<sup>5,6</sup> from signals acquired with a transducer of center frequency of about 3.5 MHz, where  $N_x$  is the number of pixels in the scan direction (around 128 pixels) and  $N_z$  is the number of pixels in the depth direction (at 40 MHz sampling rate, there will be about 10680 pixels for a depth of 200 mm in biological soft tissues). The first image can be subdivided into multiple search areas, each of which has the size of  $N_{sx} \times N_{sz}$ , where  $N_{sx}$  and  $N_{sz}$  are the number of pixels along the scan and depth directions, respectively. In the second image, kernels of the size of  $N_{kx} \times N_{kz}$  centered at the corresponding search areas of the first image can be obtained, where  $N_{kx} < N_{sx}$  and  $N_{kz} < N_{sz}$ . The sizes of

the search and the kernel areas are determined by the anticipated maximum flow velocity and resolution of the constructed velocity vector images. At a high image frame rate, the difference between the sizes of the search and kernel areas can be small (because the maximum displacement of an object may be less than 2 mm between two consecutive frames of images acquired). A small kernel size will increase the resolution in constructed velocity vector images. However, a kernel that is too small may lose the feature of the kernel leading to false correlations.

With conventional method where a digital computation is used to perform correlation integrations, it is difficult to complete all 2D correlations within a short period of time, say,  $267 \mu\text{s}$ , because there will be at least  $(N_x \times N_z)/(N_{sx} \times N_{sz})$  2D correlations. This problem may be solved with a storage correlator array modified from that shown in Fig. 1. To perform a parallel processing, more electrical and acoustical ports are added and the diode array is extended from 1D to 2D (Fig. 8).



**Figure 8.** 2D diode array for parallel 2D correlations in a modified storage correlator array.

To perform correlations, the first RF digital image constructed with the high frame rate method is read out from a random access memory (RAM) and converted to high frequency signals that match the frequency, say, 76 MHz, of the storage correlator array via  $N_r$  digital-to-analog (D/A) converters simultaneously. The analog signals are sent to the acoustic ports (Fig. 9) and stored (by applying a short strobe pulse) in parallel when they reach the end of the area of the storage diodes (mapping the entire RF image in the diode array). The kernels in the second image are then converted also to analog signals via D/A converters. The analog signals of the kernels are sent in parallel to the acoustic ports of the storage correlator array. Correlations are performed when the signals of the kernels are within their corresponding search areas of the first image stored. Correlation peaks are obtained simultaneously via the multiple electrical ports. From the positions of

correlation peaks, motion of each kernel along the depth direction can be obtained. To obtain the motions of kernels along the scan direction, the analog signals of the kernels are shifted step by step in this direction for  $N_{step} = N_{sx} - N_{kx}$  steps. The position (in both  $x$  and  $z$  coordinates) of the highest correlation peak among all steps for each kernel indicates the best possible match within the corresponding search area. From the position of the peak, the velocity vector of the kernel can be calculated.

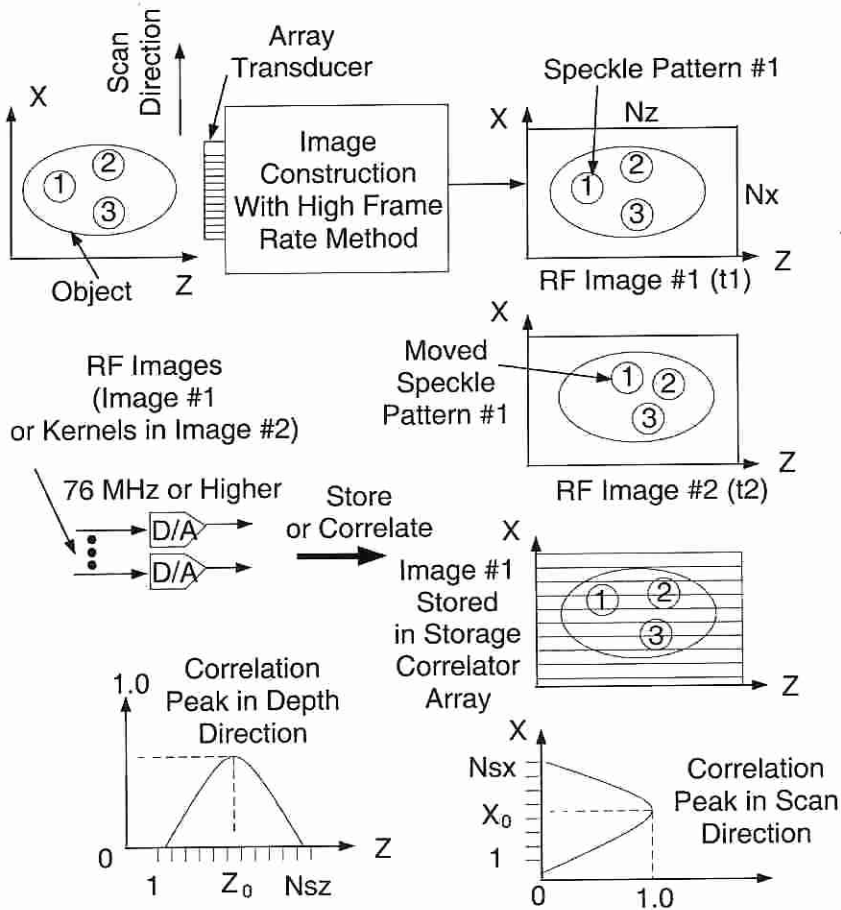


Figure 9. A schematic for parallel speckle tracking with a 2D storage correlator array.

Apparently, with the approach described above, the number of velocity vectors obtainable is equal to that of the search areas or the number of electrical ports. To increase the number of velocity vectors or improve the resolution of the constructed flow images, new kernels that lie between existing kernels and new search areas centered around these kernels can be selected. New velocity vector images can be obtained by repeating the correlation procedure above and interlacing the results with existing images.



With a higher frequency storage correlator array and a higher diode density, it is possible to obtain a high resolution velocity vector image within the time between two successive RF images (267  $\mu\text{s}$  in the example above). Assuming the depth of biological soft tissue is 200 mm, with 3.5 MHz center frequency, there will be about 933 cycles within the round trip distance of the ultrasound. After D/A conversion, the same number of cycles will be obtained but at a higher frequency, say, 76 MHz. If the high frequency signal propagates at about 4000 m/s within the storage correlation arrays, the wavelength will be 52.6  $\mu\text{m}$  and the 933 cycles will occupy a total length of about 49.12 mm. Therefore, for each correlation process, it takes about 12.28  $\mu\text{s}$  to store the first image, and additional 12.28  $\mu\text{s}$  for each step of correlation. To obtain velocity vector image of a higher resolution, the total time will be  $12.28 \times (N_{step} + 1) \times N_{off}$   $\mu\text{s}$ , where  $N_{off}$  and  $N_{step}$  are number of offsets and number of steps, respectively.  $N_{off}$  indicates the number of velocity vector images interlaced.  $N_{off}$  can be smaller if an interpolation is used to increase the pixel density of velocity vector images.

To reduce the total time required for the correlation processing, the frequency of the D/A converters can be further increased. The total length of the acoustic pathway of the storage correlator array can be reduced at a higher frequency for the same number of signal cycles. This reduces the propagation time (from 12.28  $\mu\text{s}$  in the example above). The number of diodes within the total length should be kept the same without degrading performance. The minimum number of diodes required should satisfy the Nyquist sampling rate, i.e., at least 2 diodes per cycle. For 933 cycles, the minimum of 1866 diodes are needed. With a 49.12 mm total length, the distance between the diodes must be smaller than 26  $\mu\text{m}$ . A device shown in Fig. 2 has an inter-diode distance of 8  $\mu\text{m}$ .

## DISCUSSION

In this paper we have presented an approach to perform correlations with storage correlator arrays using the space-domain processing model. The described system has the ability to construct velocity vector images in real-time.

The extension of 1D to 2D storage correlator arrays require good acoustic separation between channels. This can be accomplished by using an air kerf between channels. A pair of finger transducers is required for each channel.

Because the high frame rate imaging method developed recently can also be used to construct 3D images at an ultrahigh frame rate (a few thousand volumes per seconds), the method developed in this paper can be extended to 3D for volumetric velocity vector imaging by using more than one multi-input/output storage correlator array. Such arrays can be stacked to form a 3D storage matrix that stores an entire volume of RF image. Multiple kernels can be obtained from the second volumetric image for real-time volumetric velocity vector imaging.

## CONCLUSION

A real-time speckle tracking method using storage correlator arrays has been proposed in this paper. Previous RF speckle patterns are stored in a storage correlator array as references and current speckle patterns can be tracked in real time. The storage correlator arrays can be easily programmed, rewritten, or erased at any time. Blood flow velocity

vector images can be obtained from the correlations between the speckle patterns of previous and current RF images.

## ACKNOWLEDGMENTS

This work was supported in part by a grant HL60301 from the National Institutes of Health.

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