A Cross-Correlation Implementation of the Acoustic Location Fingerprinting Insect Detector (ALFID) System

D. Shuman[1], D. K. Weaver[1], R. W. Mankin[1], H. Chia[2],
R. E. Johnson[2], M. N. Nasah-Lima[2], R. R. Radford[2], J. S. Sun[2] and B. Weaver[1]

[1]US Department of Agriculture, Agricultural Research Service, Insects Attractants, Behavior, and Basic Biology Research Laboratory, Gainesville, FL.
[2]University of Florida, Gainesville, FL.

ABSTRACT

The automated, computer-based ALFID System was designed to quantify infestation of internally feeding larvae in a grain sample by obtaining data correlated with the location of sound sources. Initially, localization information was obtained from the relative arrival times of insect feeding sounds to an array of acoustic sensors by amplitude threshold detection. A new implementation of the ALFID System was developed to address performance problems resulting from the low signal to noise ratios and the differential distortion induced by propagation of the feeding sounds through the non-uniform grain medium to the different sensors in the array. This implementation employs computer acquisition of all sensor outputs and cross-correlation analyses of all adjacent sensor pairs in the vicinity of the sensor with the largest signal. The peak locations of the resulting cross-correlograms cluster together for multiple sounds produced by the same insect but otherwise are more broadly distributed. A cluster analysis algorithm was developed to group sounds with similar "fingerprints" (patterns of peak locations across several cross-correlograms). Each sufficiently large group of matching sounds indicates the presence of an insect.

INTRODUCTION

The presence of insects in stored grain is a major factor in the determination of quality under current mandated industry standards. Currently, grain inspection involves manually counting the insects sieved from a defined sample, usually 1 kg. This procedure limits detection to externally feeding larvae and adults. However, larvae of some economically important species, such as the rice weevil, *Sitophilus oryzae* (L.), and lesser grain borer, *Rhyzopertha dominica* (F.), feed inside kernels of grain and are not detected. If adults are not present, because they either have not yet emerged from infested kernels or have been removed by cleaning or other manufacturing processes, grain internally infested may be mistaken for uninfested grain. Current laboratory methods for the detection of internal feeders (e.g., X-ray, carbon dioxide production, resonance spectroscopy, and ELISA testing) are costly, time-consuming, and generally are not implemented (X-ray technology, which is unable to differentiate between live and dead insects, is sometimes employed by the milling industry). There is a need for a rapid, quantitative, and economical method for detecting both adults and larvae of major insect pests in grain.

Detection of insects in fruits and grain by amplifying their feeding and movement sounds was suggested by Brain (1924), but technical difficulties prevented the development of practical systems (Adams et al. 1953, Bailey & McCabe 1965, Street 1971). Recent technological advances (sensitive detectors, suitable band-pass filters, and inexpensive computers) have stimulated studies (Hagstrum et al. 1988, 1990, 1991; Vick et al. 1988) directed at the development of practical acoustic detection systems for stored-product insects (Hagstrum et al. 1994). Although the latter studies have demonstrated a strong correlation between the number of insects in a sample and total acoustical activity, it is not sufficiently accurate for the rapid grading of an unreplicated grain sample. Insect size and distance to the transducer also strongly influence infestation estimates based on the measured acoustical activity (Hagstrum & Flinn 1993). The first generation prototype Acoustic Location Fixing Insect Detector (ALFID) System endeavored to minimize the influence of these factors by determining the number of loci within a sample from which sounds were originating (Shuman et al. 1993).

The ALFID principle of operation is that the transit time of a sound is directly proportional to the distance traversed. The prototype incorporated a linear array of 16 acoustic sensors mounted in one wall of a rectangular grain sample container. By employing amplitude threshold detection of the amplified sensor outputs, it attempted to identify the first and second adjacent sensors in the array to receive a particular sound and to determine the time delay between these two detections. This would ideally localize the sound source to a (hyperbolic) surface in the grain container. The success of this method was dependent upon detecting corresponding single points on the sensors' output waveforms. However, the differences in the signal levels as a function of different source to sensor distances, the low signal to noise ratios and the differential distortion induced by propagation of the feeding sounds through the non-uniform medium to the different sensors in the array, made the time delay data unusable due to its large variability. As a result, only the identities of the first and second adjacent sensors in the array to receive a particular sound were used. Sometimes a sound was only threshold detected by one sensor which, at best, localized the sound's source within a volume twice as wide as the distance between sensors. This coarse resolution made differential detection of multiple insects or between an insect and grain settling sounds difficult. Even so, the performance of the system demonstrated conceptual feasibility and led to the development of a second-generation ALFID System whose design is described in this paper.

SECOND-GENERATION ALFID SYSTEM DESIGN

Overview

The main intent of the redesign of the ALFID system was to obtain improved sound propagation time delay data in order to increase its resolution of sound source locations. The technique of cross-correlation is well suited for extracting this time delay information when the signals are contaminated with uncorrelated noise (Helstrom 1975). It involves shifting two sensor output waveforms relative to each other along the time axis until a best fit occurs. The magnitude of the shift is the sought time delay and is based on entire signal waveforms and not just a single point on each waveform as is the case with amplitude threshold detection. This technique has been widely used for locating sound producing organisms in noisy environments with inhomogeneous sound media (Spiesberger & Fristrup 1990). This mathematically intensive approach necessitated the acquisition of the amplified sensor outputs and the subsequent computer processing of the sound data. As will be seen, it was not necessary (or practical) to locate the insects but only to discriminate and match time delay "fingerprints" unique to individual sound source locations in order to ascertain the number of sound producing insects. Hence, the name of the ALFID system was changed from the first generation prototype's "Acoustic Location Fixing Insect Detector" to the second-generation's "Acoustic Location Fingerprinting Insect Detector."

Acoustic Sensors and Amplifiers

The second-generation ALFID System uses a highly sensitive piezoelectric microphone element (Kobitone 25LM022, Mouser Electronics, Mansfield, TX). This sensor has a bandwidth of 3.5-5 kHz with a resonant peak at 4 kHz, which is a good match to the spectral content of the larval feeding sounds. A fine wire mesh over the face of the sensor helps keep grain dust out of the sound apertures in its aluminum casing. To minimize the lengths of its high impedance leads and thus reduce electromagnetic pickup, each sensor is mounted on its own amplifier circuit board. The amplifier is an impedance matching, low noise design with 85 dB of gain and some bandpass filtering (1-10 kHz).

Grain Sample Container

The ALFID system still uses a 1-kg grain sample container with an array of 16 sensors (Shuman et al. 1993), but it is now designed to maximize sensitivity throughout the volume based on the sensor's measured spatial sensitivity. It achieves this by use of a PVC cylindrical tube with an inner vinyl sound barrier layer and two rows of 8 sensors mounted directly across from each other (fig. 1). This also permits acquisition of sound data related to the source location in two orthogonal directions. During sample testing, the container is oriented horizontally with the sensors on the sides to equalize the grain pressure on the sensors. For field use, the grain container is housed in a sound attenuation box to reduce the effects of ambient noise (Mankin et al. these Proceedings). Four additional acoustic sensors are mounted on the outside of the container to provide a noise masking function discussed later.

Sound Data Acquisition

The amplified sensors' output signals are sampled and acquired by a 16 channel, 1 MHZ, D/A board (Flash-12 Model 1, Strawberry Tree, Sunnyvale, CA) installed into a PC computer (fig.

2) and controlled by a custom designed software driver. The insect sounds occur randomly and can last up to 20 ms (due to grain ringing). A larva (fourth instar) will typically produce less than 5 detectable sounds/minute. For this reason, in order to not fill the PC's memory with incoming background noise, the D/A board is configured to transfer data being acquired into its own ring buffer memory to the PC's memory only when the board is triggered by a sufficiently loud sound. Since the identity of the sensor channel with a signal large enough to cause triggering is unknown, a trigger generation circuit was designed to logically "OR" the output of all the amplified sensors' outputs. A generated trigger signal that rises above the board's trigger input amplitude threshold level initiates the transfer of all 16 sensors' acquired output signals, including channels with signals that may remain below this threshold level (fig. 3), to the PC's memory. Once triggered, the board's trigger input is disabled so that subsequent peaks of a sound's received waveforms (as manifest in the trigger signal) do not initiate further data transfers to the PC's memory until the system is ready for a new sound.

The grain sample test duration is an input variable for the custom software driver that controls the data acquisition operation of the ALFID system. A longer test duration increases the probability that an insect will be detected (but slows down the throughput of grain samples) and typically range from 10 to 30 minutes.

A noise masking feature (fig. 2) was designed to reduce the possibility of loud ambient sounds not sufficiently blocked by the sound attenuation box from being interpreted as an insect sound. If the outputs of any of four acoustic sensors mounted on the outside of the grain container are amplitude threshold detected, an inhibit signal is generated which blocks the transfer of the acquired ambient sound data (in the D/A board's ring buffer) to the PC's memory.

The key part of the sensors' output signals for determining the propagation time delay are the first few cycles of the sound because they are less likely to be contaminated by multipath and reflected waves or the lower frequency resonant "ringing" of the grain. To insure acquisition of these first few cycles, the D/A board is configured to provide pretrigger data. It is continuously acquiring sampled sensors' output signal data into a ring buffer memory so that new data is overwriting recently (as a function of sampling rate and memory size) acquired data. When a trigger occurs, an additional 2 ms of sampled signal data is written into the ring buffer memory. The board then transfers 4 ms of this sampled data to the PC, beginning with sampled data that was written into the ring buffer 2 ms before the time that the trigger occurred (time = 0 in fig. 3). The sampling rate of the D/A board is set to 62.5 kHz/channel to provide a 16 μs time shift resolution for the cross-correlation analysis. Therefore an acquired 4 ms block of data fills 4k samples of buffer memory. To insure no loss of data due to the relatively slow transfer rate of data from the A/D board's buffer memory to the PC's memory in the event of a burst of insect sounds, the A/D board hardware was custom modified to segment its 64k sample ring buffer into 16 4k sample ring buffers, each independently addressable and able to store a full 4 ms block of data. The A/D board hardware was also custom modified to re-enable its trigger input only after 7 ms have elapsed since the last time the trigger signal exceeded its threshold level. This feature prevents a single long sound whose generated trigger signal stays below the trigger amplitude threshold level for short durations (less than 7 ms) from being interpreted as multiple sounds. Since the sound data acquisition software is driven by interrupts generated by the trigger signal, future versions of the system could potentially begin analysis of the data during the PC's relatively idle periods between insect sounds.

Culling and Cross-correlation (XC) Analysis

The XC of two sensors' output signals in discrete (digitized) form, A(I) and B(I) where I is the sample number, is described by the equation:

$$R_{A\times B}(j) = \sum_{k=1}^{N} A(k)\,B(k+j)$$

where j is the number of shifts of A relative to B, and N is the total number of samples of each signal. The range of j depends on the extent of time delay that needs to be considered. For the sensor spacing in the grain container and the speed of sound propagation in the grain, the j values required are only from -32 to 32 shifts corresponding to -512 to 512 µs. The value of N is 250 samples for the 4 ms interval of acquired sound. Digitized signal values for sample numbers outside range of 1-250 were zero-padded. The direct method of calculating the XC with this equation (as opposed to the "short" FFT method) is more efficient for the small values of N and j. The plot of this equation is referred to as the cross-correlogram (fig. 4) and the time location of its peak indicates the time delay for a best fit of the sound waveforms. With 16 sensors arranged in two lines of 8 sensors, there are 36 possible contiguous sensors pairs, including adjacent (14), across (8), and diagonal (14) pairs, for which XCs can be calculated (fig. 5). These XCs provide information related to a sound's source location in only two dimensions, but the redundancy of the diagonal pairs can help with fingerprinting in this low signal/noise context.

Ideally, samples of all 16 sensors' output signals would be obtained simultaneously to prevent time skew errors in the cross-correlograms. However, the A/D board chosen uses sequential sampling with a 1 µs sampling period. For the 36 possible contiguous sensors pairs used, the maximum XC time skew error is 9 µs (e.g., for 2 X 11). With a cross-correlogram resolution of 16 µs, the resulting maximum absolute error in peak time locations is 1 data point or 16 µs. However, the error would be consistent for multiple sounds from the same source location, and so it would not effect the matching of these sounds.

The cross-correlograms usually have two to four peaks (fig. 4) within their -512 µs to 512 µs time delay window due to the periodic nature and spectral content of insect sound waveforms. The true peak, having a time location corresponding to a sound source's true location, does not necessarily have the largest amplitude because of differences in waveform shapes (from a single sound emanation) on the outputs of different sensors (fig.3). For this reason the two largest peaks are considered, to increase the probability that at least one of them will match in time delay with a peak on subsequent sounds produced by the same insect. It is because of these multiple peaks that the true source location is indeterminate. That is, if all the unculled (see below) peaks in all the cross-correlograms resulting from a sound were used in an attempt to establish its source location (by a mathematical analysis similar to triangulation), the result would be a multiplicity of virtual locations. However, the consistency of cross-correlogram peak time locations across sounds produced by one insect (fig 6), especially when observed for several different sensor pairs, supports the methodology of using a fingerprint for each acquired sound consisting of two peak time delay locations for each sensor pair XC. It is for these reasons that the original goal of "fixing" a sound source's location to be compared with the locations of other sounds was aborted in favor of establishing a "fingerprint" related to a sound source's location to be compared to the fingerprints of other sounds, all for the purpose of matching sounds that are from the same source.

When the output of a sensor that is mostly or entirely noise is used in an XC calculation, the result is a cross-correlogram with peaks in random locations. With a large collection of sounds, some of these random peak locations could erroneously match different sounds' fingerprints together, giving incorrect assessment of insect infestation. To reduce this occurrence, various methods of culling potentially problematic data are incorporated.

Two methods of culling a subset of sensor channels are employed prior to the XC analysis. Insect sounds generally reach only a few of the nearby sensors and so, for the 8 sensors on each side of the grain container, only the sensor with the largest RMS amplitude signal and its two adjacent sensors are considered for a maximum of 6 out of 16 sensor channels (fig. 5). Also, for any one of these 6 sensor channels to be used, its output signal must first pass a check for an acceptable signal to noise ratio. This is accomplished by specifying a minimum acceptable value (e.g., 1.4) for the ratio of the RMS amplitude of a later segment of the waveform where the sound would be expected to be found to the RMS amplitude of an initial pretrigger segment of the waveform where only the channel's noise output would be present (fig. 3). The location of these segments and the minimum RMS ratio value can be adjusted to empirically optimize the system's performance for a given hardware implementation (Weaver et al. these Proceedings).

After the XC analysis is performed, cross-correlogram peaks are culled based on their amplitudes and time delay values. Peaks with amplitudes below a specified absolute value, indicating a questionable best fit of shifted waveforms, are culled. Also, for each acquired sound, peaks with amplitudes below a specified percentage of the largest cross-correlogram peak amplitude obtained with that sound are culled. This compensates the amplitude culling for the loudness of a sound, which is beneficial because the XC of a large sound signal on one channel with a purely noisy output on another channel can still result in substantial peak amplitudes. These absolute and relative peak amplitude culling thresholds can also be adjusted to empirically optimize the system's performance for a given hardware implementation (Weaver et al. these Proceedings). Cross-correlogram peaks are also not used if their time delay values are greater than what is physically possible, given the distances between sensors and the speed of sound propagation in the grain. By substituting the next smaller peak for one known to be false, this time delay boundary (which is empirically determined independently for adjacent, across, and diagonal sensor pairs) increases the probability that one of the two peaks used is the true peak and therefore provides a more reliable fingerprint of the sound. It has also been observed that if the number of peaks in a cross-correlogram is greater than 5, it is a good indication that one of the employed sensor channel outputs is predominantly noise and this cross-correlogram is therefore culled.

Cluster Analysis and Fingerprint Grouping Algorithm

The XC analysis provides a fingerprint for each acquired sound that consists of up to two peak time delay values for a subset of the 36 possible XCs. Each XC is treated as an independent dimension. For the fingerprints of any two individual sounds to be considered a match (meaning they emanated from the same source location), their peak time delay values should match (within some amount of variability) within several different XC dimensions. A number of sounds from the same source location should form clusters within these XC dimensions. A cluster analysis and fingerprint grouping algorithm was developed on the premise that the matching of individual sounds can be inferred from their peak locations being members of the same clusters.

The first step in the algorithm is the plotting of the cumulative peak distribution (CPD) for each XC dimension (fig. 7). To determine whether a scattering of peaks is due to sounds emanating from different source locations (and should not be clustered together) or due to the expected variability from a single source location (and should be clustered together), a distribution of cross-correlogram true peak locations was empirically derived from 2200 sounds acquired with single insects (fourth instars of the rice weevil, *Sitophilus oryzae* (L.)) at various locations in a grain sample container filled with wheat. Individually obtained distributions were aligned (to compensate for different insect locations) along centroids that evenly split their areas, and then summed. The resulting composite discrete distribution was best matched by a Gaussian Lorentzian Cross Product distribution which was then normalized (fig. 8). More than 90% of the correlogram true peak locations from single insects are within a window that is 8 sample periods (i.e., encompassing 9 discrete sample points) or 128 µs wide.

Based on a potential field density method for delineating clusters (Massart & Kaufman 1989), a discrete version of this normalized distribution was selected as a potential function. A potential field contour (PFC) is constructed by replacing each sound in a CPD with this potential function and summing the results at each discrete time delay value (fig. 9). Each valley of a PFC is checked for validity as a cluster boundary based on a set of rules involving the valley's height relative to the height of adjacent PFC peaks. For a resulting excessively wide cluster domain (delineated by a pair of cluster boundaries), which could erroneously link sounds emanating from different source locations, a maximum cluster-width window is positioned along the Relative Time Delay axis of the PFC to encompass the maximum number of sounds (fig. 10). The width of this window can be adjusted to empirically optimize the system's performance, a tradeoff between false positives and false negatives in detecting insects (Weaver et al. these Proceedings). Finally, only clusters that contain some minimum number of sounds are considered valid. This minimum cluster membership criterion can also be adjusted and is set with regard to the grain sample test duration.

When all the valid clusters in all the XC dimensions, and their constituent sounds, have been identified, a matching matrix is created to quantify the fingerprint match between every combination of two acquired sounds (fig 11). In the matching matrix, each pair of sounds is assigned a matching value equal to the number of clusters (a maximum of one per XC dimension) within which both are members. A pair of sounds that has a matching value equal or greater than the matching value threshold (can be adjusted, Weaver et al. these Proceedings) are considered to have been generated by the same source and are grouped together. This grouping process reduces the matching matrix to a set of groups where each sound is present in only one group and a group can have any number of sounds. Each group with some minimum number of sounds (a function of test duration) is considered to indicate the presence of an insect. This minimum group size is adjustable (Weaver et al. these Proceedings) and its optimal value varies with test duration since an insect generally produces more sounds over time.

Status

The ALFID System described here has a number of parameters whose values were initially selected to provide an operational baseline and then were empirically adjusted to optimize performance (Weaver et al. these Proceedings). Future research will focus on further tuning of the system, establishing performance abilities in the laboratory, and field testing it at a commercial grain elevator.

Acknowledgments

We thank the Federal Grain Inspection Service, Kansas City, MO for their interest and support of this project. This research was supported in part by a specific cooperative agreement between the United States Department of Agriculture and the Agricultural and Biological Engineering Department at the University of Florida.

REFERENCES

Adams, R. E., J. E. Wolfe, M. Milner & J. A. Shellenberger. 1953. Aural detection of grain infested internally with insects. Science (Washington, DC) 118: 163–164.

Bailey, S. W. & J. B. McCabe. 1965. The detection of immature stages of insects within grains of wheat. J. Stored Prod. Res. 1: 201–202.

Brain, C. K. 1924. Preliminary note on the adaptation of certain radio principles to insect investigation work. Ann. Univ. Stellenbosch Ser. A 2: 45–47.

Hagstrum, D. W., J. C. Webb & K. W. Vick. 1988. Acoustical detection and estimation of Rhyzopertha dominica (F.) larval populations in stored wheat. Fla. Entomol. 71: 441–447.

Hagstrum, D. W., K. W. Vick & J. C. Webb. 1990. Acoustical monitoring of Rhizopertha dominica (Coleoptera:Bostrichidae) populations in stored wheat. J. Econ. Entomol. 83: 625–628.

Hagstrum, D. W., K. W. Vick & P. W. Flinn. 1991. Automated acoustical monitoring of Tribolium castaneum (Coleoptera: Tenebrionidae) populations in stored wheat. J. Econ. Entomol. 84: 1604–1608.

Hagstrum, D. W., and P. W. Flinn. 1993. Comparison of acoustical detection of several species of stored-grain beetles (Coleoptera: Curculionidae, Tenebrionidae, Bostrichidae, Cucujidae) over a range of temperatures. J. Econ. Entomol. 86: 1271–1278.

Hagstrum, D. W., P. W. Flinn, & D. Shuman. 1994. Acoustical monitoring of stored-grain insects: an automated system. Proc. 6th Intern. Working Conf. on Stored-Product Protection. Canberra, Australia. 1: 403-405.

Helstrom, C. W. 1975. Statistical theory of signal detection. Pergamon, New York.

Mankin, R. W., J. S. Sun, D. Shuman, & D. K. Weaver. 1995. A sound-insulated enclosure to shield acoustical insect detectors from grain elevator background noise. Proceedings of the Second Symposium on Agroacoustics, National Center for Physical Acoustics, University of Mississippi, September 6-7, 1995: xxx-xxx.

Massart, D. L. & L. Kaufman. 1989. The interpretation of analytical chemical data by the use of cluster analysis. R. E. Krieger, Florida.

Shuman, D., J. A. Coffelt, K. W. Vick, & R. W. Mankin. 1993. Quantitative acoustical detection of larvae feeding inside kernels of grain. J. of Econ. Entomol. 86 (3): 933-938.

Spiesberger, J. L. & K. M. Fristrup. 1990. Passive localization of calling animals and sensing of their acoustic environment using acoustic tomography. The American Naturalist. 135: 107-153.

Street, W. M., Jr. 1971. A method for aural monitoring of in-kernel insect activity. J. Ga. Entomol. Soc. 6: 72–75.

Vick, K. W., J. C. Webb, B. A. Weaver & C. Litzkow. 1988. Sound detection of stored-product insects that feed inside kernels of grain. J. Econ. Entomol. 81: 1489–1493.

Weaver, D. K., D. Shuman, R. W. Mankin, R. E. Johnson, M.N. Nasah-Lima, R. R. Radford, H. Chia, and B. Weaver. 1995. Performance of an algorithm based on cross-correlations which detects the number of infested wheat kernels in grain samples tested in ALFID. Proceedings of the Second Symposium on Agroacoustics, National Center for Physical Acoustics, University of Mississippi, September 6-7, 1995: xxx-xxx.

FIGURE CAPTIONS

Figure 1 Mechanical drawing of the ALFID Grain Container.

Figure 2 ALFID System Functional Block Diagram.

Figure 3 Typical signal waveforms from a single insect sound as seen on the amplified outputs of different sensors. The stored data begins 2 ms before, and ends 2 ms after, when acquisition triggering occurs.

Figure 4 Cross-correlograms calculated from the sensor outputs shown in Figure 3. The full time delay window used in the XC analysis (-512 µs to 512 µs prior to imposing the time delay boundaries) is not shown.

Figure 5 Depiction of different contiguous sensors pairs for which XCs are calculated, including adjacent, across, and diagonal pairs. To cull potentially error producing data, only the sensors with the largest RMS signal outputs on each side (for each acquired sound), and those adjacent to them, determine the subset (e.g., the 11 pairs shown) of XCs to be considered.

Figure 6 Cross-correlograms calculated from a single pair of sensor outputs for multiple sounds produced by the same insect. The peaks tend to be aligned with each other.

Figure 7 A typical cumulative peak distribution (CPD) in one XC dimension, obtained with a grain sample containing one infested kernel.

Figure 8 Empirically derived normalized distribution of XC true peaks consolidated from tests with single insects at various locations. This distribution, shown with 99% prediction intervals, is used as the potential function to create potential field contours (PFC).

Figure 9 A typical potential field contour (PFC), derived from the CPD in Figure 7.

Figure 10 Delineation of cluster domains from the PFC in Figure 9. The boundaries of the cluster centered about -192 µs were set using a maximum cluster-width window of 128 µs.

Figure 11 Example of the fingerprint matching algorithm with six acquired sounds. For three XC dimensions, clusters with their constituent sounds are displayed. The derived matching matrix shows three pairs of sounds with sufficient matching values for grouping. They form a single group of sounds that meets the minimum group size criterion, thus indicating the presence of an insect in the sample.

ALFID GRAIN CONTAINER

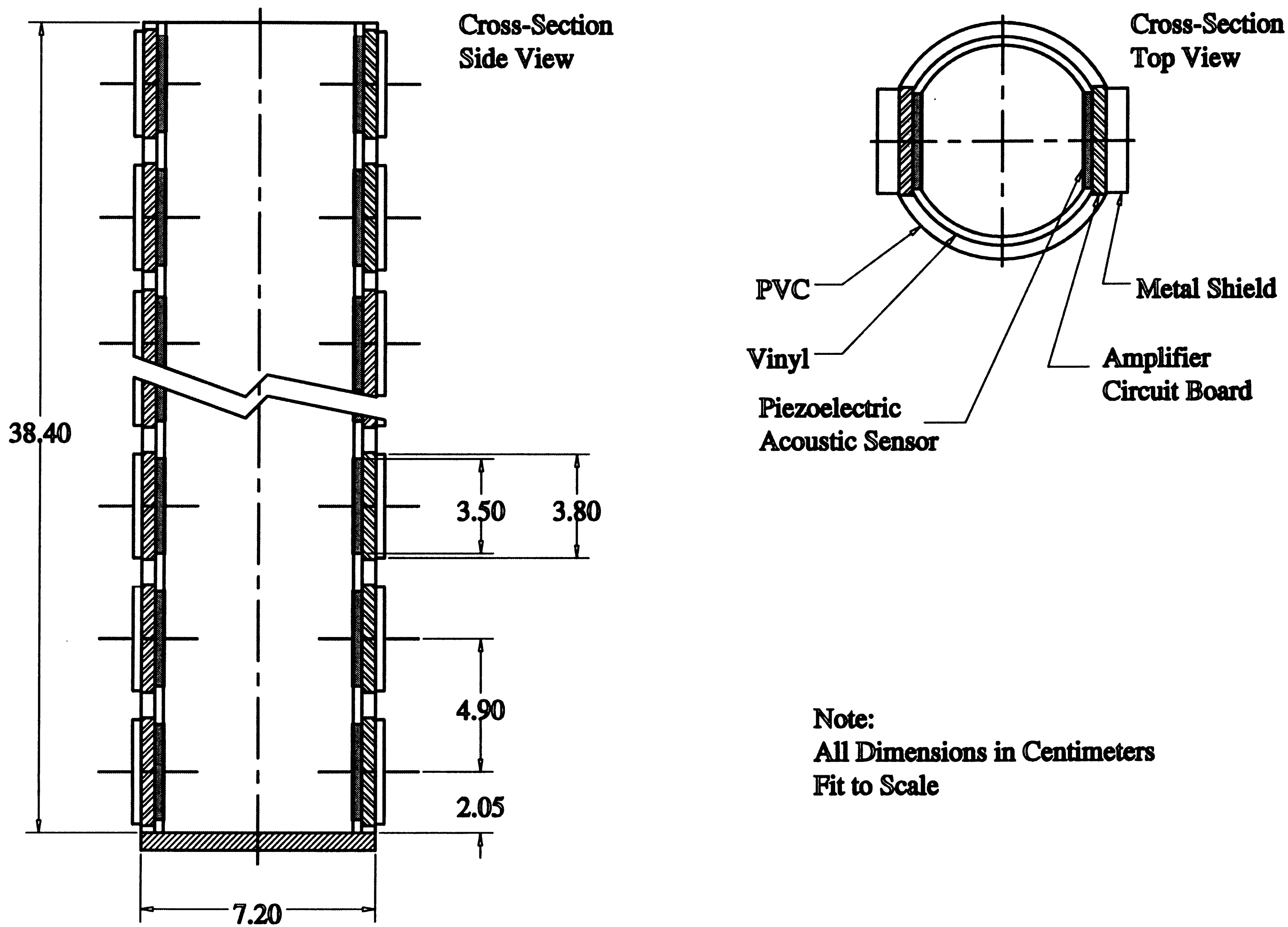


Figure 1

ALFID System Functional Block Diagram

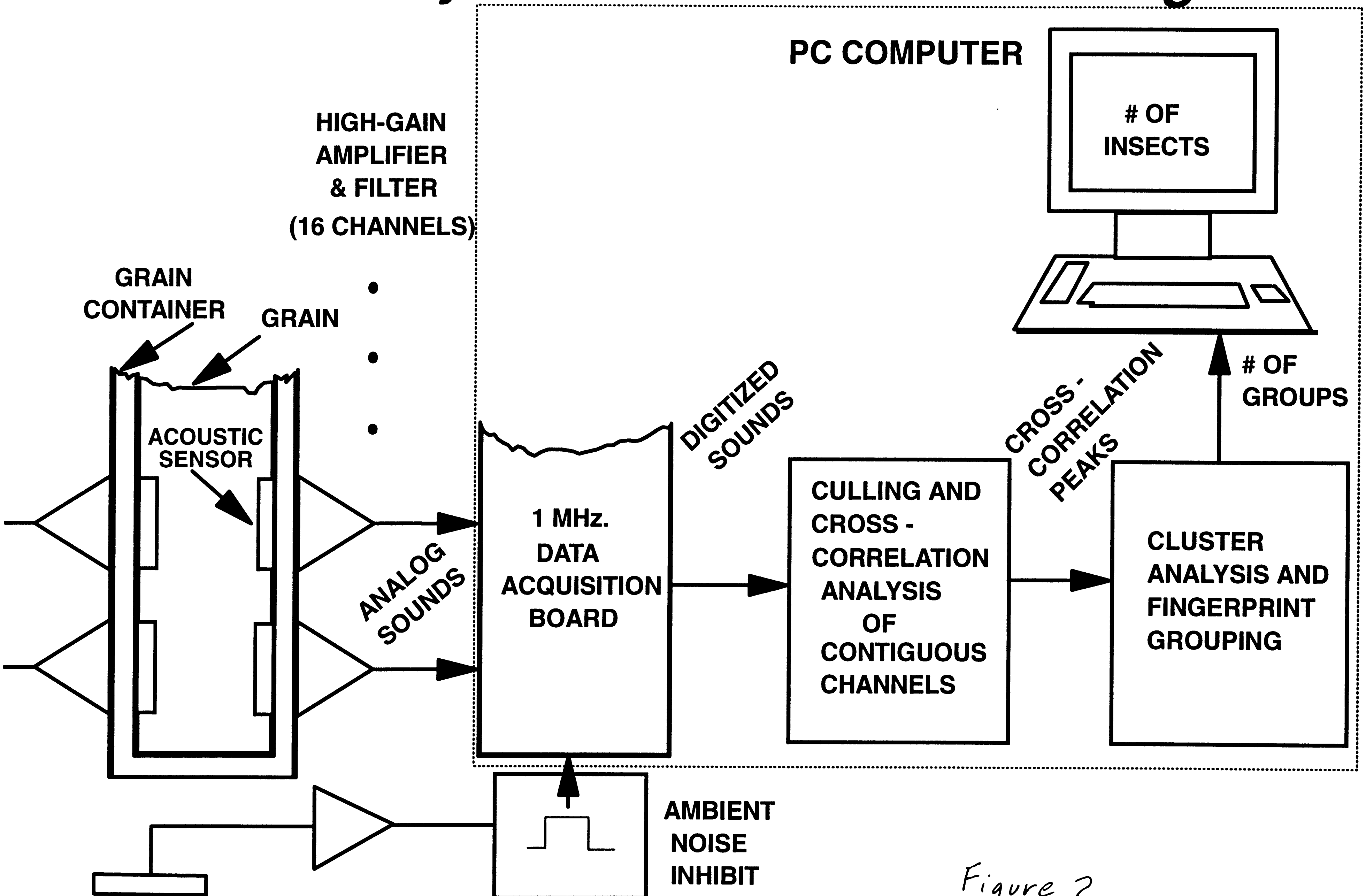


Figure 2

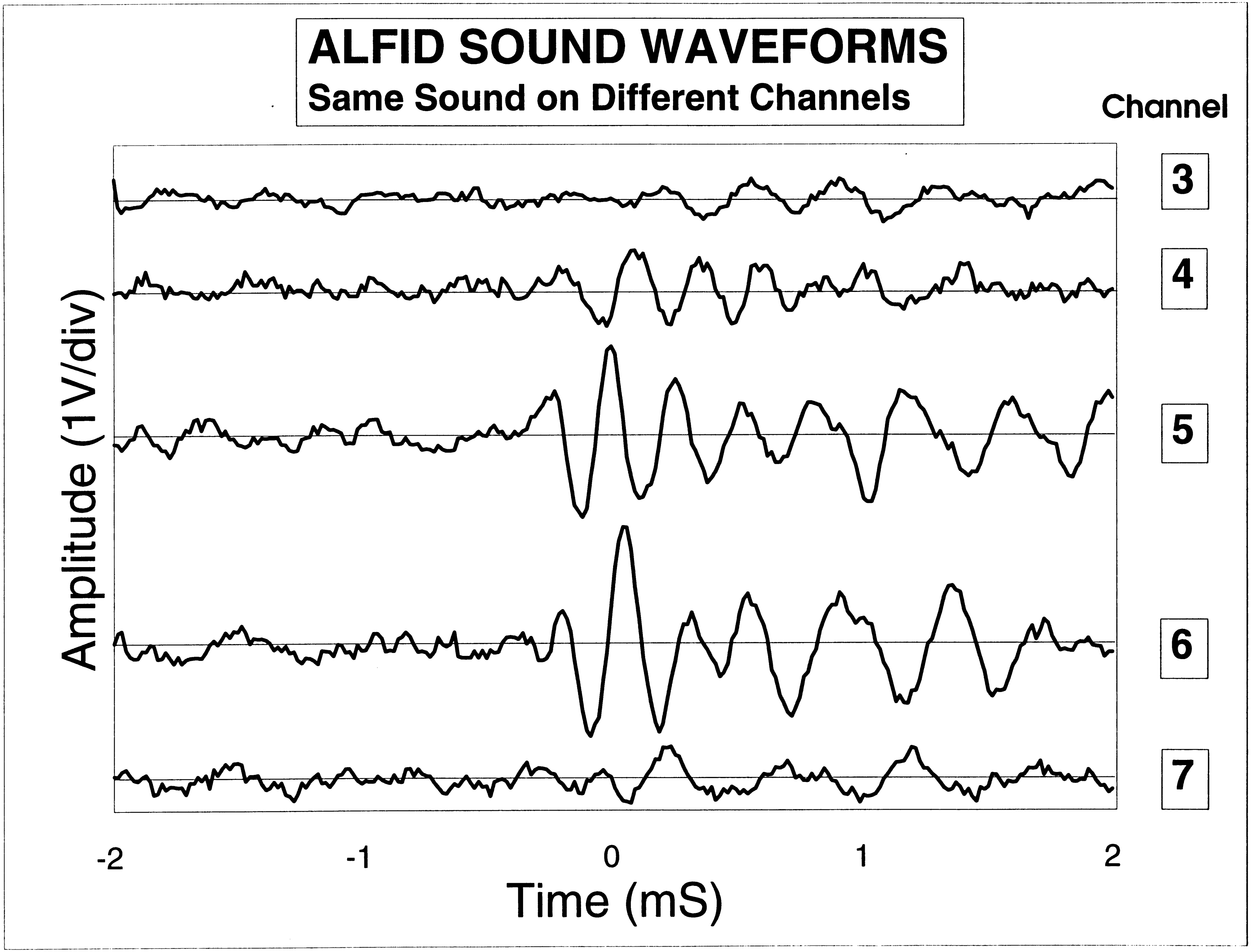

ALFID SOUND WAVEFORMS
Same Sound on Different Channels
Channel
3
4
5
6
7
Amplitude (1V/div)
-2
-1
0
1
2
Time (mS)

Figure 3

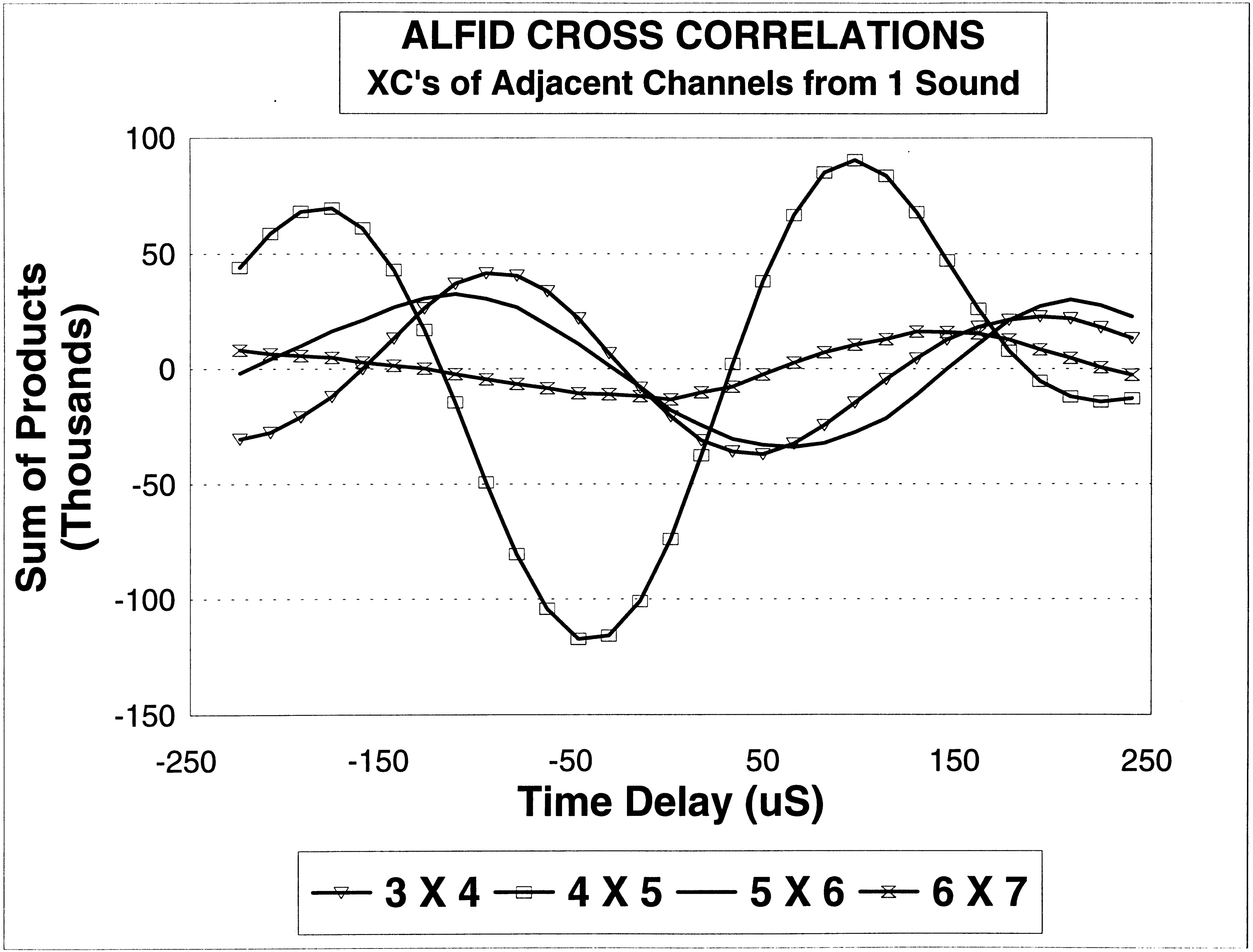

ALFID CROSS CORRELATIONS
XC's of Adjacent Channels from 1 Sound
100
50
0
-50
-100
-150
Sum of Products (Thousands)
-250
-150
-50
50
150
250
Time Delay (uS)
3 X 4
4 X 5
5 X 6
6 X 7

Figure 4

ALFID CROSS-CORRELATIONS USED (36)

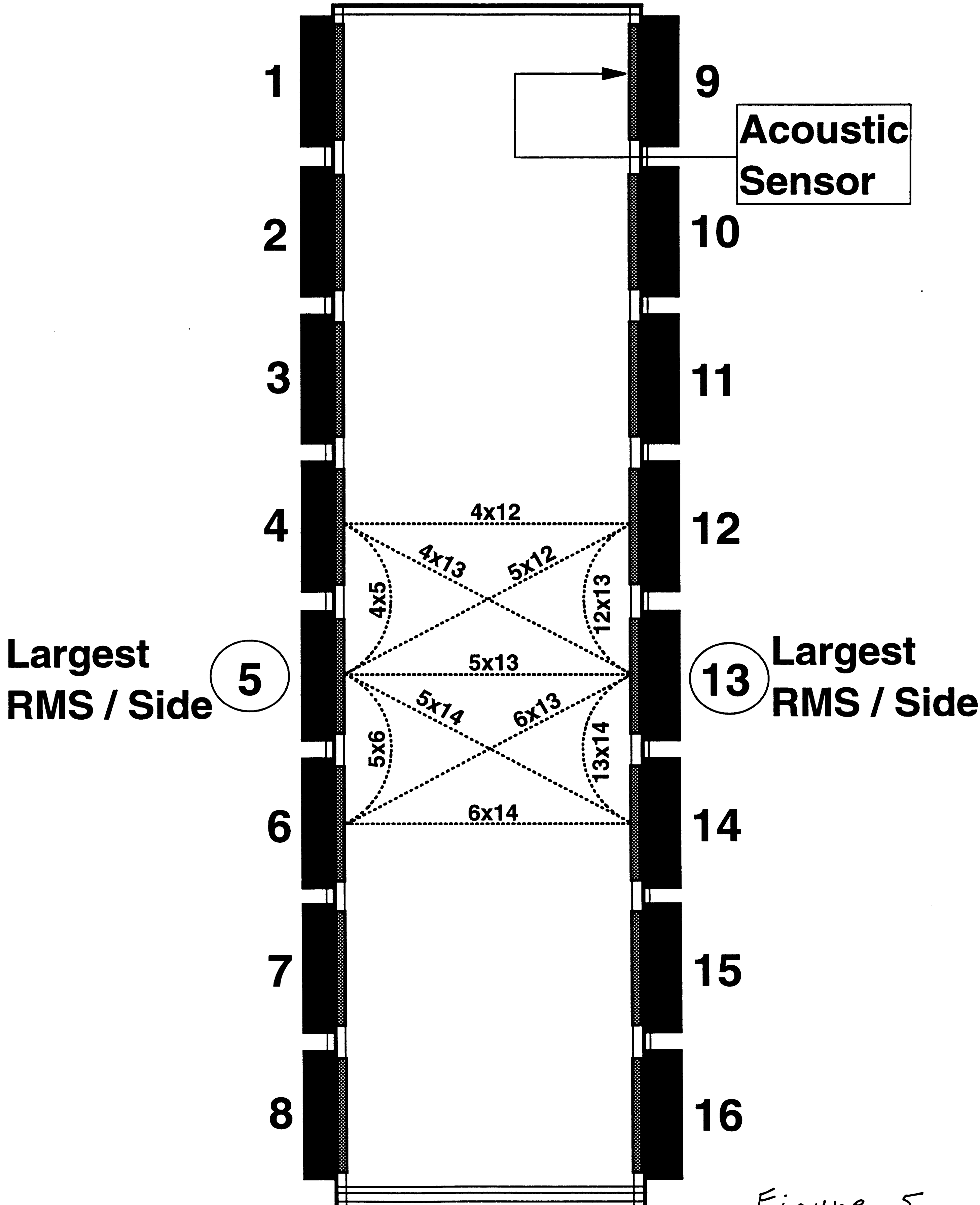


Figure 5

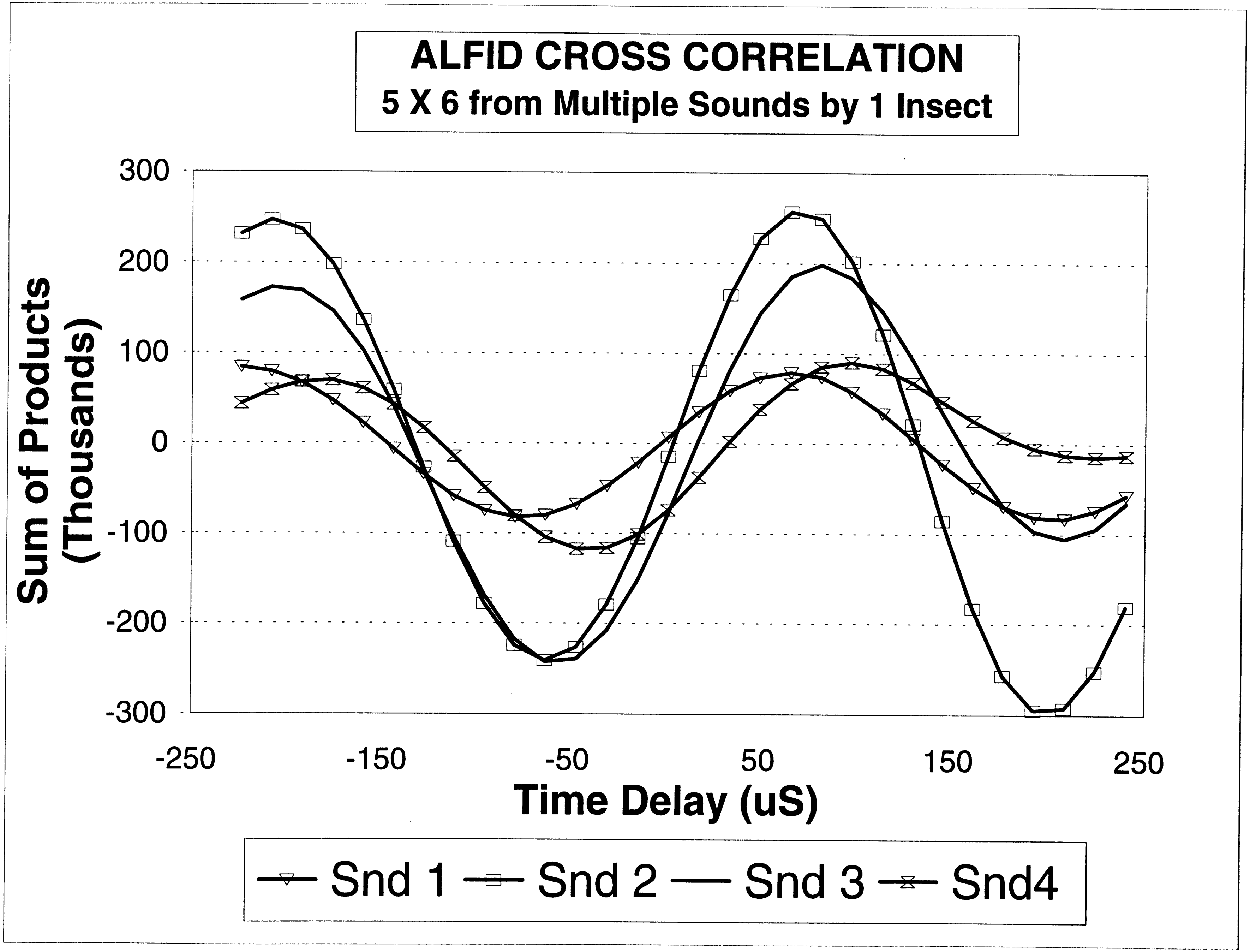

ALFID CROSS CORRELATION
5 X 6 from Multiple Sounds by 1 Insect
Sum of Products (Thousands)
300
200
100
0
-100
-200
-300
-250
-150
-50
50
150
250
Time Delay (uS)
Snd 1
Snd 2
Snd 3
Snd4

Figure 6

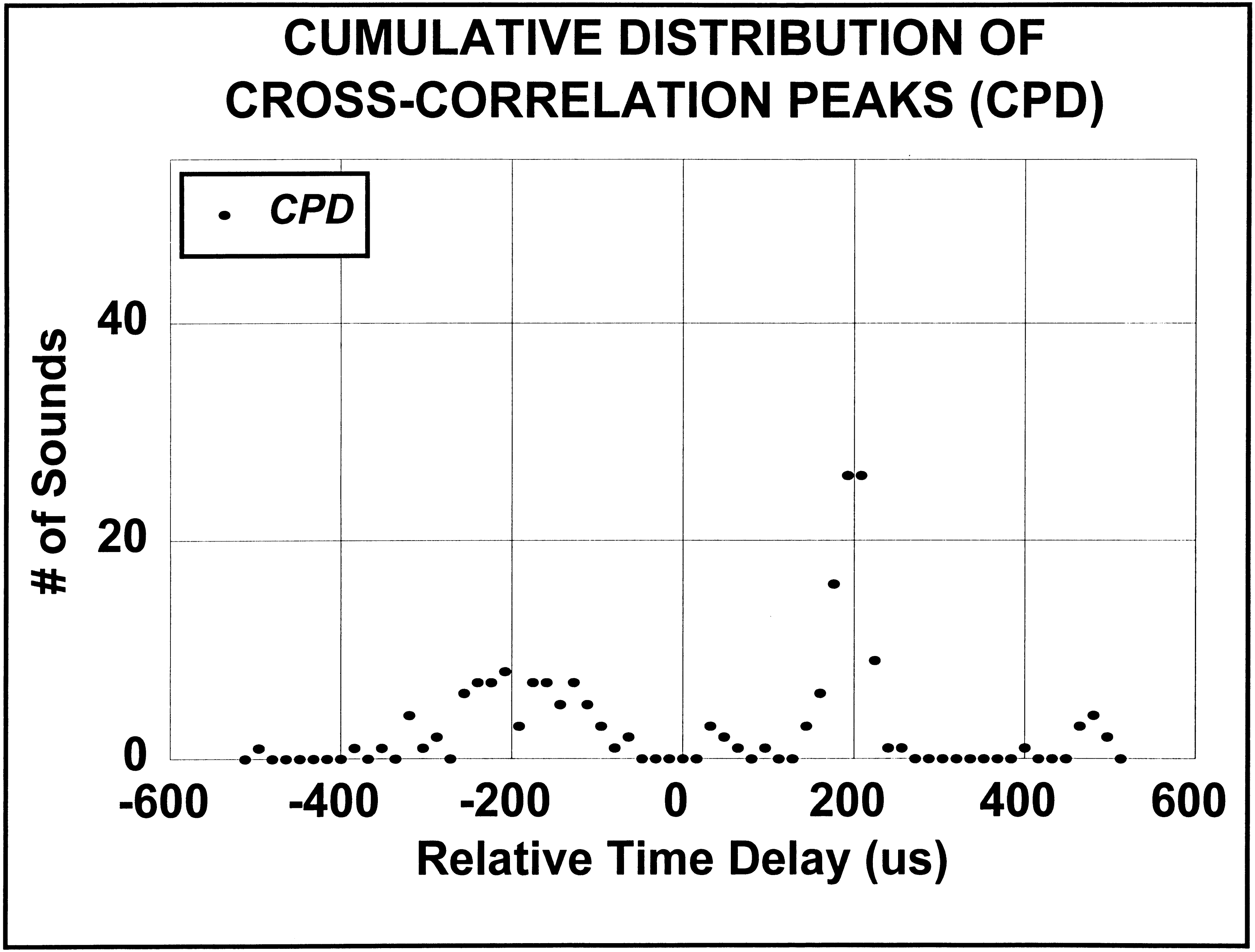

CUMULATIVE DISTRIBUTION OF
CROSS-CORRELATION PEAKS (CPD)
CPD
# of Sounds
0
20
40
-600
-400
-200
0
200
400
600
Relative Time Delay (us)

Figure 7

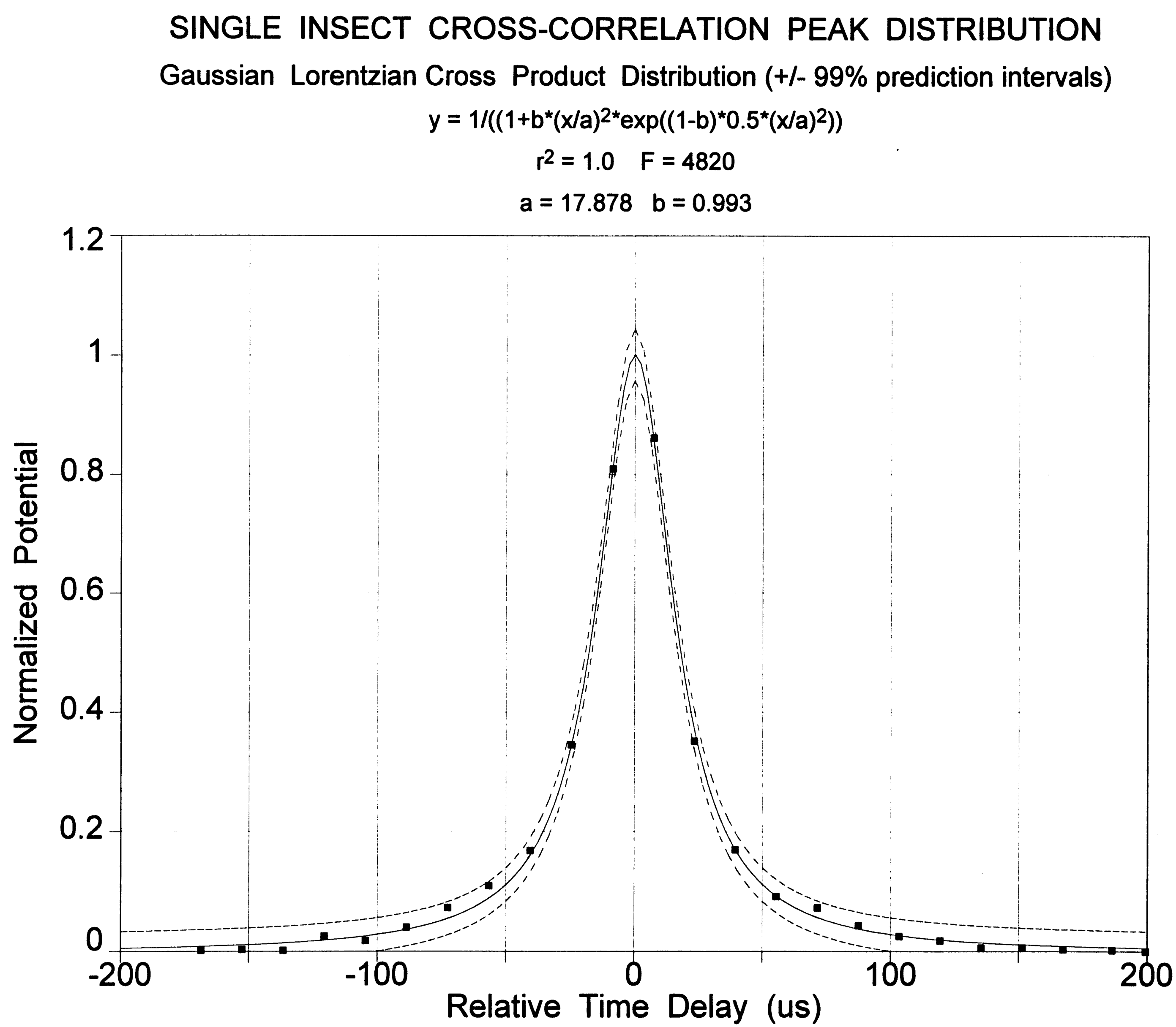

SINGLE INSECT CROSS-CORRELATION PEAK DISTRIBUTION
Gaussian Lorentzian Cross Product Distribution (+/- 99% prediction intervals)
y = 1/((1+b*(x/a)^2*exp((1-b)*0.5*(x/a)^2))
r^2 = 1.0 F = 4820
a = 17.878 b = 0.993
1.2
1
0.8
0.6
0.4
0.2
0
Normalized Potential
-200
-100
0
100
200
Relative Time Delay (us)

Figure 8

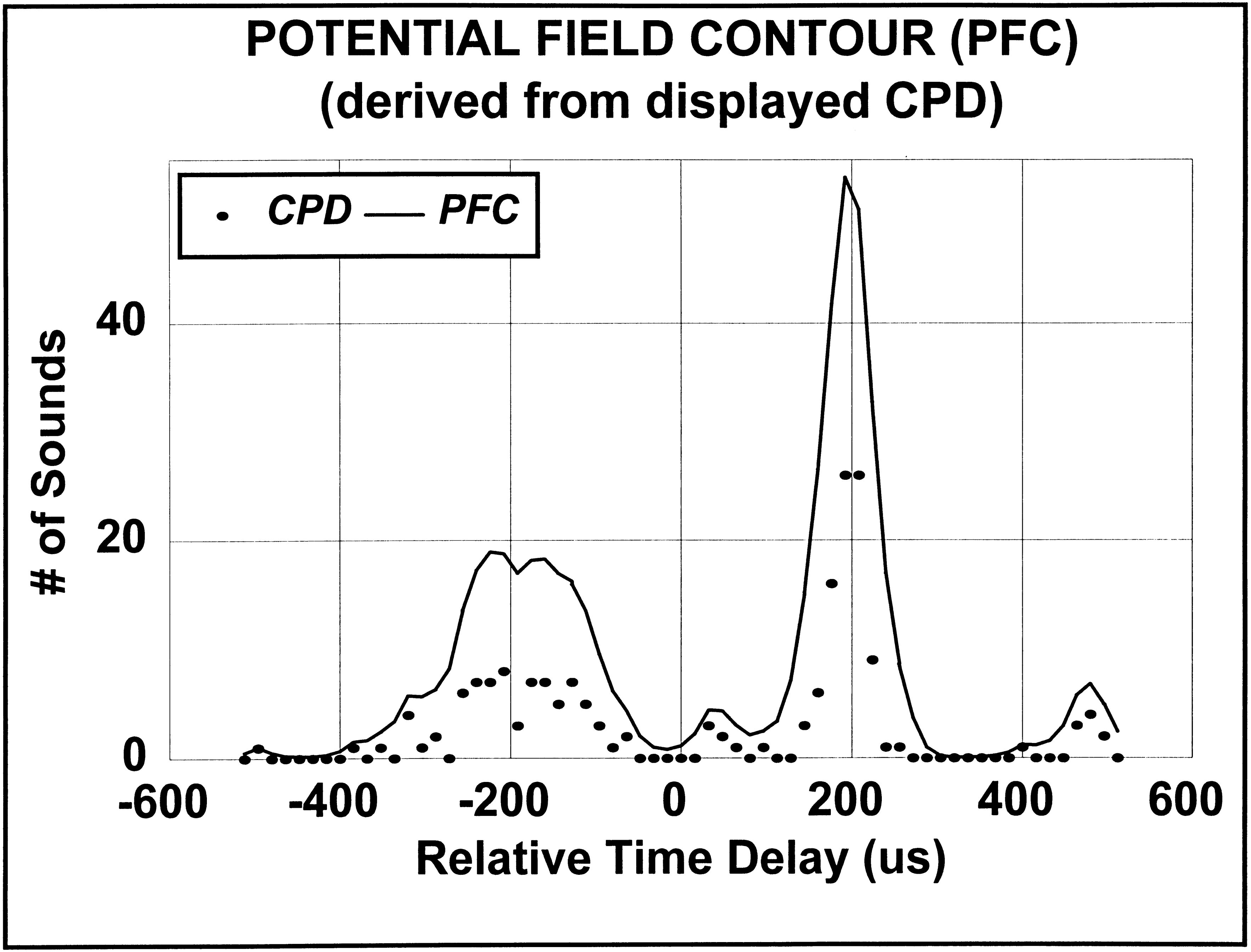

POTENTIAL FIELD CONTOUR (PFC)
(derived from displayed CPD)
CPD
PFC
# of Sounds
40
20
0
-600
-400
-200
0
200
400
600
Relative Time Delay (us)

Figure 9

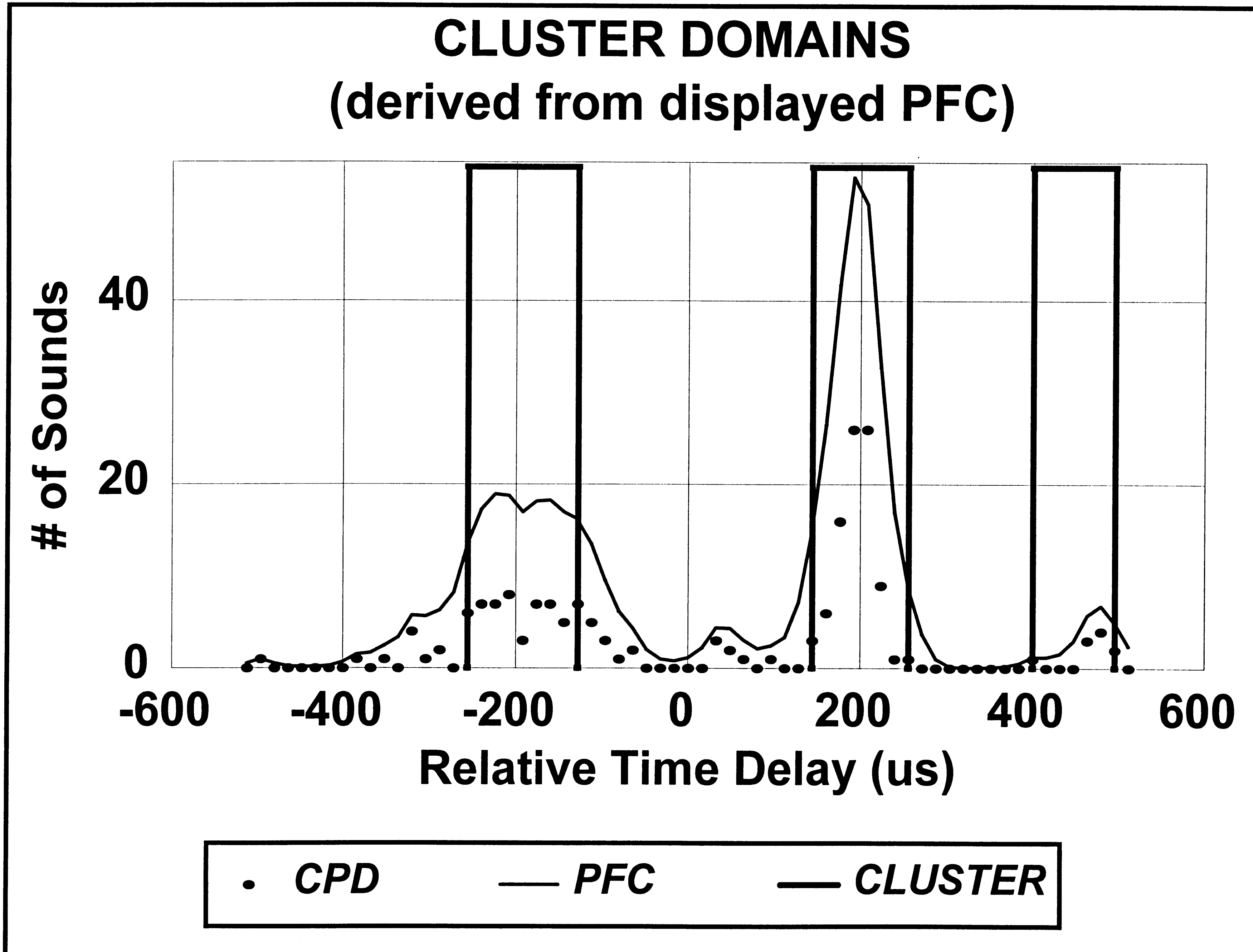
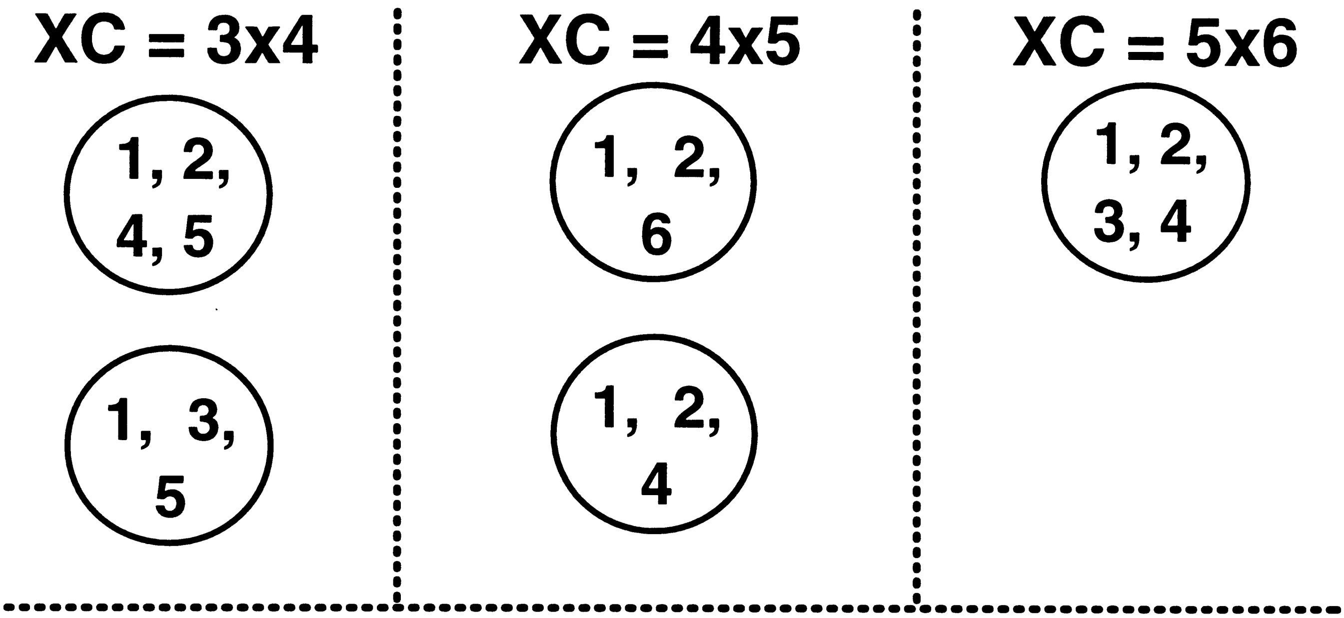

CLUSTER DOMAINS
(derived from displayed PFC)
# of Sounds
40
20
0
-600
-400
-200
0
200
400
600
Relative Time Delay (us)
CPD
PFC
CLUSTER

Figure 10

FINGERPRINT MATCHING

Cluster Sounds



Matching Matrix

	1	2	3	4	5	6
1	-	(3)	2	(3)	1	1
2		-	1	(3)	1	1
3			-	1	1	0
4				-	1	0
5					-	0
6						-

If
Matching Value
Threshold = 3
Then Group = 1, 2, 4

If Minimum Group Size = 3
Then 1Insect Present

Figure 11