A SOFTWARE PACKAGE FOR ESTIMATING TIME DIFFERENCES FOR ARTILLERY SOUND RANGING APPLICATIONS

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Prepared by
LONNIE C. LUDEMAN
Electrical and Computer Engineering Department
New Mexico State University
Las Cruces, New Mexico 88003

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CONTRACT MONITOR: BERNARD ENGEBOS

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Destroy this report when it is no longer needed. Do not return it to the originator.
The Fortran program entitled "Time Differences Estimator Program" is presented and documented. The program will accept a given number of microphone signals each containing a specified number of data points from a fixed data format and determine the time differences between signal bursts that appear within the record length. It also gives a measure of reliability to associate with the time differences and provides, through a least square error procedure, a consistent set of relative times that can be used as input data to a position...
estimator. Results from using the program on a number of recorded signals from C4 explosions approximately 12 km away are presented showing target location errors of approximately 200 meters.
ACKNOWLEDGEMENT

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**TABLE OF CONTENTS**

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>ACKNOWLEDGEMENT</td>
<td>iii</td>
</tr>
<tr>
<td>I. INTRODUCTION</td>
<td>1</td>
</tr>
<tr>
<td>II. GENERAL DESCRIPTION TIME DIFFERENCES ESTIMATOR PROGRAM</td>
<td>2</td>
</tr>
<tr>
<td>A. Initialization and Acceptance of Data</td>
<td>2</td>
</tr>
<tr>
<td>1. Initializing</td>
<td></td>
</tr>
<tr>
<td>2. Data File Format</td>
<td></td>
</tr>
<tr>
<td>3. Bringing in Data from Master File</td>
<td></td>
</tr>
<tr>
<td>B. Determination of Time Windows and Energies</td>
<td>7</td>
</tr>
<tr>
<td>1. Computation of Rough Arrival Times</td>
<td></td>
</tr>
<tr>
<td>2. Computation of Fourier Window Starting Points</td>
<td></td>
</tr>
<tr>
<td>3. Computation of Signal Energy within Fourier Window</td>
<td></td>
</tr>
<tr>
<td>C. Prefiltering Operation</td>
<td>8</td>
</tr>
<tr>
<td>1. Determination of Starting Point for Noise Window</td>
<td></td>
</tr>
<tr>
<td>2. Determination of Estimate of Noise Spectrum</td>
<td></td>
</tr>
<tr>
<td>4. Computation of Prefilter Values</td>
<td></td>
</tr>
<tr>
<td>5. Application of Prefilter</td>
<td></td>
</tr>
<tr>
<td>6. Application of Comb Filter for 60 HZ and Harmonics</td>
<td></td>
</tr>
<tr>
<td>D. Pair by Pair Correlation</td>
<td>12</td>
</tr>
<tr>
<td>1. Positioning of Signals for Determining the Cross Correlation</td>
<td></td>
</tr>
<tr>
<td>2. Finding the Raw Time Differences between Windowed Signals</td>
<td></td>
</tr>
<tr>
<td>3. Determination of the Normalized Correlation Coefficient</td>
<td></td>
</tr>
<tr>
<td>4. Determination of the Rough Time Differences between Signals I and L</td>
<td></td>
</tr>
<tr>
<td>E. Determination of Least Square Time Fit</td>
<td>14</td>
</tr>
<tr>
<td>1. Establishment of Weights for Least Square Time Fit</td>
<td></td>
</tr>
<tr>
<td>2. Determination of Least Square Time Fit with MIC 1 as a Reference</td>
<td></td>
</tr>
<tr>
<td>3. Adjustment of Time Differences</td>
<td></td>
</tr>
<tr>
<td>4. Selection of MIC to be used as Reference</td>
<td></td>
</tr>
<tr>
<td>5. Determination of Relative Times for the Position Estimator</td>
<td></td>
</tr>
<tr>
<td>F. Printing the Output</td>
<td>18</td>
</tr>
<tr>
<td>1. Shot Information</td>
<td></td>
</tr>
<tr>
<td>2. Window Information</td>
<td></td>
</tr>
<tr>
<td>3. Time Differences Information</td>
<td></td>
</tr>
<tr>
<td>4. Met and Timing for Position Estimator</td>
<td></td>
</tr>
</tbody>
</table>
LIST OF FIGURES

Figure Page
1. Processing Structure of the Time Differences Estimator Program 3
2. Illustration of the Data File Format 5
3. Example of the Program Output Format 19
4. Results from PASS Shot S1-D341-MB-1 21
5. Results from PASS Shot S1-D341-MB-2 22
6. Results from PASS Shot S2-D341-MB-1 23
7. Results from PASS Shot S2-D341-MB-2 24
8. Results from PASS Shot S2-D341-MB-4 25
9. Results from PASS Shot S3-D341-MB-2 26
10. Results from PASS Shot S7-D341-MB-2 27

List of Tables

Table Page
1. Comb Filter Frequency Bands 12
2. PASS Data Shots Used in Program Testing 20
3. Miss Distances for PASS Data Examples 28
1. INTRODUCTION

The main problem of sound ranging is to determine the location of a transient sound source by examining the signals received at an array of microphones. The problem can be logically broken down into two main parts. First the determination of the relative arrival times of the sound at the microphones and second, the use of this information to estimate the position. In this paper we concentrate on the determination of relative arrival times.

In the past, the arrival times at each microphone were determined by visually selecting a point of charge, the so-called "break point", from strip chart recorded signals [1]. Some methods used to determine these break points have been: first inflection, first maximum after inflection and first cross over after inflection. A comparative study of these methods is given in Dean [2]. In contrast to the break point methods, the author [3] proposed a procedure to obtain more accurate timing information from the received microphone signals by using the correlation between signals. The method when implemented on a digital computer would not only speed up the determination of the relative arrival times but provide more accurate results with less chance for reading errors than the visual techniques.

The purpose of this paper is to document a Fortran realization of the correlation technique described in [3] and present results from using field data from the PASS [4] experiment as input. These limited results indicate that, under a controlled experimental environment, the overall method provides reasonably good time differences estimates which, when used with the proper meteorological data, give good position estimates.
II. GENERAL DESCRIPTION OF TIME DIFFERENCES ESTIMATOR PROGRAM

The overall structure of the computer program for determining the relative time differences consists of the following basic sections: (A) Initialization and acceptance of input data, (B) a determination of the time windows that would enclose the signal received from the source and a calculation of the energies within the windows, (C) a prefiltering operation that would overcome wind and extraneous noise, (D) a pair by pair correlation to determine a rough time difference and a measure of correlation, (E) the determination of an overall least square time fit, and (F) an outputting of results. A general flow chart indicating processing structure is given in Figure 1, the program listing is given in Appendix A, and each main block is described in detail in the following sections. Each of the subheadings under the main blocks are set apart by comment cards in the program for ease in presentation.

A. Initialization and Acceptance of Data

1. Initializing. In the initialization portion of the program there are a number of parameters that must be specified and dimensioned. The main parameters are:

NMIC = Number of microphones
NL = Number of data points for each microphone
NSW = Number of points in the sliding window
NPFW = number of points in the Fourier window

The number of points in the sliding window is chosen to be approximately the number of points in the expected signal. By examining the C4 data from the PASS experiment, an example of which appears in Appendix C, it was seen that signals were in the 300-375 msec length and at a sample rate of 1 K samples/second this means approximately 350 samples. The number of points in the Fourier window was selected to be 1.5 times the number in the sliding
MICROPHONE SIGNALS

INITIALIZATION AND
ACCEPTANCE OF DATA

SHOT INFORMATION

DETERMINATION
OF TIME WINDOWS
AND ENERGIES

PREFILTERING
OPERATION

WINDOW INFORMATION

PAIR BY PAIR
CORRELATION

CORRELATION
COEFFICIENTS

ROUGH TIME
DIFFERENCES

DETERMINATION
OF LEAST SQUARE
TIME FIT

METEOROLOGICAL
INFORMATION

CORRECTED TIME
DIFFERENCES

POSITION ESTIMATOR
TIMES

Figure 1. Processing structure of the Time Differences Estimator Program
window to make sure that most of the signal was within the window. For the
C4 this meant approximately 500, and since the Fourier transform can be ob-
tained faster for powers of 2 by the FFT, NPFW was selected to be 512 and
NWS = 342. The data files provided by personnel from the Physical Sciences
Laboratory (PSL), Las Cruces, New Mexico, were constructed to be 1920 samples
per signal in length; therefore, NL is set equal to 1920. The following
dimension and complex cards would then be required:

```fortran
DIMENSION IDAY(NMIC), IHOUR(NMIC), IMIN(NMIC), SEC(NMIC), MIC(NMIC), TIME(NMIC)
DIMENSION TAU(NMIC,NMIC), IT(NMIC), NR(NMIC), E(NMIC), RTAU(NMIC,NMIC),
CTAU(NMIC,NMIC), CAM(NMIC,NMIC)
DIMENSION SMIC(NMIC,NL,LRST(NMIC, G(NMIC,NMIC), AT(NMIC), A(NMIC,NMIC),
JC(NMIC-1), V(2)
DIMENSION CMMEAS(NMIC), MCOM(11).
CMPLEX X(2·NPFW), Y(2·NPFW), WORK(2·NPFW), XX(2·NPFW), YY(2·NPFW), ZZ(2·NPFW)
```

2. Data file Format. The input to the program was data taken from the
PASS Experiment that had been transferred to files in the UNIVAC 1108 system by PSL
personnel. The format modified slightly to include MET data and file identi-
fication for these data files is illustrated in Figure 2. Each data file is
728 lines in length with the first eight lines containing timing and shot in-
formation while the remaining lines contain the data for each microphone. To
be more specific in the format we have the following line by line structure.

```
12 12 13 12 12 F6.3 F4.1 I4 I4 I4
```

Line 1: 6 1 341 12 36 2.024 06.7 6380 09

a = Number of microphones
b = PASS source number
c = Day of Pass shot
d = Hour of Pass shot
e = Min of Pass shot
Figure 2. Illustration of Data File Format
\( f \) = Second of Pass shot
\( g \) = Effective temperature in Deg C. for shot
\( h \) = Wind direction in MILS
\( i \) = Wind speed in KNOTS

Line 2: SOURCE 1 MIKE ARRAY B FILE (S1-D341-MB-1.)

\( a \) = Number of microphones
\( b \) = Indication of source position, microphone array and file identification

Lines 3-8: MICROPHONE INDEX 1920 120 27 341 12 36 35.611

\( a \) = Microphone index \( J \)
\( b \) = Number of values per microphone in record
\( c \) = Number of lines of data for each microphone
\( d \) = PASS microphone number: \( \text{MIC}(J) \)
\( e \) = Starting day of microphone record
\( f \) = Starting hour of microphone record
\( g \) = Starting min of microphone record
\( h \) = Starting second of microphone record

Line 9: \[ a_1 \quad a_1 \quad a_1 \quad a_1 \]

\( a_i \) = value of microphone 1 at time \( i = 1, \ldots, 16 \)

Line 10: \[ a_i \quad a_i \quad a_i \quad a_i \]

\( a_i \) = value of microphone 1 at time \( i = 17, \ldots, 32 \)

Line 128: \[ a_i \quad a_i \quad a_i \quad a_i \]

\( a_i \) = value of microphone 1 at time \( i = 1905, \ldots, 1920 \)
In a similar fashion

Lines 129-248: values of microphone 2 at times \( i = 1, 2, \ldots, 1920 \)

249-368: values of microphone 3 at times \( i = 1, 2, \ldots, 1920 \)

369-488: values of microphone 4 at times \( i = 1, 2, \ldots, 1920 \)

489-608: values of microphone 5 at times \( i = 1, 2, \ldots, 1920 \)

609-728: values of microphone 6 at times \( i = 1, 2, \ldots, 1920 \)

3. Bringing in Data from Master File. In the original version of the program a subroutine was provided by PSL to read the data files and transfer this information to the SMIC(J,I) indexed array. In the present version the new subroutine RDATA(SMIC,MIC,IDAY,IHOUR,IMIN,SEC,TEMP,MILS,KNOTS) was written to obtain a desired output format and include meteorological and other cataloging information. A Fortran listing of the subroutine appears in Appendix B. To bring in the data to the program arrays simply requires the Fortran statement:

```
CALL RDATA(SMIC,MIC,IDAY,IHOUR,IMIN,SEC,TEMP,MILS,KNOTS)
```

The indexed arrays: SMIC, MIC, IDAY, IHOUR, IMIN, SEC are described in the previous section and represent the values and starting time information for each microphone signal, while the TEMP, MILS, and KNOTS are defined below.

- **TEMP** = Effective temperature at the time of the shot in degrees Centigrade
- **MILS** = The angle of wind in mils at the time of the shot
- **KNOTS** = The speed of the wind at the time of the shot

B. Determination of Time Windows and Energies

In many cases the time intervals of the received signals are much larger than the transient signal searched for and if the correlation procedure is used on the entire length of each signal an exorbitant amount of time would be consumed. Therefore, windows are established around the location of the signal bursts. This part of the procedure consists of computing rough arrival times, starting points for windows and the energies within the windows.
1. Computation of Rough Arrival Times. The rough arrival times are determined by the use of an energy detector for each signal. That is the energy within a sliding time window \((I, I+\text{NSW})\) is calculated for all values of time \(I\) equal to \(NL-\text{NSW}\). The point in time \(I_{\text{MAX}}\) for the Jth microphone signal where the energy is maximum is called the rough starting time \(LRST(J)\). If \(X(J,I)\) \(I = 1,2,\ldots,\text{NL}\) is the input to the energy detector for the Jth signal, the running value of the energy within the Jth sliding window becomes

\[
E(J,I) = \sum_{k=I}^{I+\text{NSW}} \text{SMIC}^2(J,k) \quad I = 1,2,\ldots,\text{NL}-\text{NSW}
\]

\(LRST(J)\) = value of \(I\) such that \(E(J,I)\) is maximized.

2. Computation of Fourier Window Starting Points. The starting point \(\text{NR}(J)\) for the Jth signal Fourier window is selected by bracketing the rough starting time on both sides by \(\text{NSW}/4\). Care must be taken to make sure that the beginning and ending points of the window remain within 1 and \(\text{NL}\). This is done by making the following assignment for \(\text{NR}(J)\).

\[
\text{NR}(J) = \begin{cases} 
1 & \text{if } LRST(J) - \text{NSW}/4 \leq 1 \\
LRST(J) - \text{NSW}/4 & \text{if } 1 < (LRST(J)-\text{NSW}/4) \leq \text{NL} - 3\text{NSW}/2 \\
\text{NL}-3\cdot\text{NSW}/2 & \text{if } (LRST(J)-\text{NSW}/4) > \text{NL} - 3\text{NSW}/2 
\end{cases}
\]

3. Computation of Signal Energy within the Fourier Window. Once \(\text{NR}(J)\) has been determined the energy within each Fourier window can be calculated as follows:

\[
E(J) = \sum_{k=\text{NR}(J)}^{\text{NR}(J)+3\text{NSW}/2} \text{SMIC}^2(J,k)
\]

The starting point of the Fourier window and signal energy are then printed out for each microphone.

C. Prefiltering Operation

In many cases there is noise present on the lines during the duration of the signals. The noise could come from a wide variety of sources including
wind noise, sixty cycle interference, and machine related noise. To characterize all these noises analytically becomes almost impossible. The program was designed, however, to try to minimize the effects these noises would have by prefiltering the data. This was done by using estimates of the spectrum of the noise, and the spectrum of the signal plus noise.

1. Determination of Starting Point for Noise Window. The noise window for each signal, selected to be before the Fourier window which contains the signal plus noise, consists of 512 points consistent with the Fourier window in size. By keeping the windows the same size the determination of the prefilter and application of the prefilter is simplified. The starting point for the noise window for each signal was determined by

\[
\text{Start Point (J)} = \text{NR(J)} - 512
\]

If this was less than zero for some J then the starting point for the Jth noise window was set equal to the first data point of that signal record. Since most of the data records had over 500 samples, i.e. 500 msec worth of noise preceding the signal, few cases of signal and noise window overlaps were reported.

2. Determination of Estimate of Noise Spectrum. For each pair of signals SMIC(I,L) and SMIC(J,L), and respective noise window starting points KXX and KYY, a rough estimate of the noise spectrum is desired. The estimation procedure used was that of obtaining the spectrum for each signal and simply averaging the results. To provide a spectrum compatible in samples the FOURG SUBROUTINE was used on each of the following signal vectors.

\[
\begin{align*}
\text{XX} & = [\text{SMIC(I,KXX)}, \text{SMIC(I,KXX+1)}, \ldots, \text{SMIC(I,KXX+511)}, 0, 0, \ldots, 0] \\
\text{YY} & = [\text{SMIC(J,KYY)}, \text{SMIC(J,KYY+1)}, \ldots, \text{SMIC(J,KYY+511)}, 0, 0, \ldots, 0]
\end{align*}
\]

The addition of zeros will not alter the spectrum determined and provide the proper frequency indices. The spectrum was then estimated by
Spectrum for noise = \[ \frac{\text{FOURG}(XX) \cdot \text{FOURG}^*(XX) + \text{FOURG}(YY) \cdot \text{FOURG}^*(YY)}{2} \]

The noise spectrum was stored back in the real part of the complex array YY(L), L = 1,2,..., 1024.

3. Determination of Estimate of Signal Plus Noise Spectrum. For each pair of signals SMIC(I,L) and SMIC(J,L) and respective Fourier window starting points NR(I) and NR(J) the following signal vectors were defined.

\[
\begin{align*}
XX &= [\text{SMIC}(I,NR(I)), \text{SMIC}(I,NR(I)+1), ..., \text{SMIC}(I,NR(I)+511), 0, 0, ..., 0] \\
ZZ &= [\text{SMIC}(J,NR(J)), \text{SMIC}(J,NR(J)+1), ..., \text{SMIC}(J,NR(J)+511), 0, 0, ..., 0]
\end{align*}
\]

The signal plus noise spectrum was stored back in the real part of complex array XX(L), L = 1,2,..., 1024.

4. Computation of Prefilter Values. The prefilter that is to be applied to each pair of signals was selected to be of the form

\[ H(L) = \frac{\phi_{ss}(L)}{(\phi_{ss}(L) + \phi_{nn}(L))} \quad L = 1,2,..., 1024 \]

where \( \phi_{ss}(L) \) and \( \phi_{nn}(L) \) represent the value of the energy spectrum density of signal and noise respectively at index L. Since the \( \phi_{ss}(L) \) was not known the prefilter frequency response was written in the following equivalent form

\[ H(L) = 1 - \frac{\phi_{nn}(L)}{(\phi_{ss}(L) + \phi_{nn}(L))} \]

Since only the estimates of \( \phi_{nn}(L) \) and \( \phi_{ss}(L) + \phi_{nn}(L) \) are available, care must be taken to insure that \( H(L) \) does not go negative. The program uses \( \text{Real}(XX(L)) \) and \( \text{Real}(YY(L)) \) to represent \( \phi_{ss}(L) + \phi_{nn}(L) \) and \( \phi_{nn}(L) \) respectively and defines \( \text{PRC} \) and \( \text{PRD} \) as

\[ \text{PRC} = \frac{\text{REAL}(YY(L))}{\text{REAL}(XX(L))} \]

\[ \text{PRD} = \text{REAL}(XX(L)) \]

The prefilter value ZZ(L) at frequency index L is described as follows for \( L = 1,2,..., 1024 \).
If PRC > 1

\[ ZZ(L) = \begin{cases} 
(0,0) & \text{if PRD} < .001 \\
(1,1) & \text{otherwise} \\
\text{CMPLX}(H(L),H(L))
\end{cases} \]

5. Application of Prefilter. Once the prefilter values have been determined and the product of the DFT of each positioned signal is eventually put in \( Y(L) \) \( L = 1,2,...,1024 \) the prefiltering operation is done simply by multiplying each frequency component by \( ZZ(L) \) that is

\[ ZZ(L) = \text{CMPLX} (\text{PREF},\text{PREF}) \]

\[ Y(L) = Y(L) \times ZZ(L) \]

6. Application of Comb Filter for 60 HZ and Harmonics

The power spectral density was obtained for microphone noise signals from the PASS experiment showing dc power, power in 60 HZ and harmonics, some low frequency wind noise, and some unidentified interference of approximately 7.8 HZ and higher harmonics. An example appears in Appendix C. To minimize the effects of these interferences a comb filter including a low pass filter was applied in the frequency domain. For the 1024 point Fourier transform the frequency indexes and corresponding analog and digital frequencies are given by:

<table>
<thead>
<tr>
<th>index</th>
<th>digital frequency</th>
<th>corresponding analog frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>( k )</td>
<td>((k-1) \cdot 2\pi/1024 ) radians</td>
<td>((k-1) \cdot 2\pi/1024T ) radian/sec</td>
</tr>
</tbody>
</table>

Since the time \( T \) between samples is 1 msec for the PASS data the corresponding analog frequencies are spaced \( 2\pi/1024 \) rad/sec or .97656 HZ apart. The D.C. component index is one. Since 60 HZ and harmonics do not fall exactly on index numbers this causes a leakage to a band of frequencies that must be considered. The apparent index given in Table 1 is determined by:

\[ \text{Apparent index} = \text{freq.}(1.024) + 1. \]

The upper index band required because of symmetry of the DFT is determined by

\[ k_u = 2 \ast \text{NPFW} + 2 - k = 1026 - k \]
TABLE 1 Comb Filter Frequency Bands

<table>
<thead>
<tr>
<th>Identification</th>
<th>Frequency Band</th>
<th>Apparent Index</th>
<th>Lower Index Band k</th>
<th>Upper Index Band k_U</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>D.C.</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>b</td>
<td>0^+ - 7.8 Hz</td>
<td>1-8.9</td>
<td>2-10</td>
<td>1016-1024</td>
</tr>
<tr>
<td>c</td>
<td>60 Hz</td>
<td>62.44</td>
<td>60-65</td>
<td>961-966</td>
</tr>
<tr>
<td>d</td>
<td>120 Hz</td>
<td>123.88</td>
<td>121-126</td>
<td>900-905</td>
</tr>
<tr>
<td>e</td>
<td>180 Hz</td>
<td>185.32</td>
<td>183-188</td>
<td>838-843</td>
</tr>
<tr>
<td>f</td>
<td>140 Hz</td>
<td>246.76</td>
<td>244-249</td>
<td>777-782</td>
</tr>
</tbody>
</table>

The index information for the comb filter was given in the following data card:

```
| DATA MCOMB/1, 2, 10, 60, 65, 122, 126, 183, 188, 244, 249/
| a h c d e f |
```

The comb filter was applied by setting the values corresponding to the index bands equal to zero in the frequency domain output of the pair by pair correlation.

D. Pair by Pair Correlation

The pair by pair cross correlation \( R_{xy}(L) \) of the windowed signals is accomplished in the frequency domain by use of the FFT algorithm. That is

\[
R_{xy}(L) = \text{IDFT} \left[ \text{DFT}(X(L)) \cdot \text{DFT}^*(Y(L)) \right]
\]

Since the above operation performs circular correlation it is necessary to position the data signals \( X(L) \) and \( Y(L) \) such that the circular and linear correlation are the same. The * means complex conjugate and is needed to provide correlation rather than convolution.

1. Positioning of Signals for Determining the Cross Correlation. To obtain linear convolution resulting in proper correlation, the signals SMIC(I,L)
and \( \text{SMIC}(J,L) \) \( L = 1,2,\ldots,512 \) are positioned as follows

\[
\begin{array}{cccccccc}
L & 1 & \cdots & 2 & \cdots & 512 & 513 & 514 & \cdots & 1024 \\
\text{Real } X(L) & \text{SMIC}(I,1), & \text{SMIC}(I,2), & \ldots, & \text{SMIC}(I,512), & 0 & 0 & \cdots & 0 \\
\text{Imag } X(L) & 0 & 0 & \cdots & 0 & 0 & 0 & \cdots & 0 \\
\text{Real } Y(L) & 0 & 0 & \cdots & 0 & \text{SMIC}(J,1), & \text{SMIC}(J,2), & \ldots, & \text{SMIC}(J,512) \\
\text{Imag } Y(L) & 0 & 0 & \cdots & 0 & 0 & 0 & \cdots & 0 \\
\end{array}
\]

2. Finding the Raw Time Differences between Windowed Signals. Once the \( \text{DFT}(X(L)) \cdot \text{DFT}^*(Y(L)) \) is prefiltered and comb filtered the cross correlation \( R_{xy}(L) \) is obtained back in the real part of array \( Y(L) \) \( L=1,2,\ldots,1024 \) by taking the Inverse Fourier Transform. The Fortran statement uses a +1 to indicate inverse as follows.

\[
\text{CALL FOURG}(Y,1024,+1, \text{WORK})
\]

A search is then performed on \( |\text{Real}(Y(L))| \), \( L=1,2,\ldots,1024 \) to obtain the maximum value \( \text{CMAX} \) of the cross correlation and the time \( \text{TMAX} \) of the maximum value. Because of the positioning of the signals the raw time difference is then given by

\[
\text{TAU}(I,J) = \text{TMAX} - \text{NPFW} - 1
\]

3. Determination of the Normalized Correlation Coefficient. The normalized correlation coefficient \( \text{GAM}(I,J) \) is obtained by dividing the maximum value by the square root of the product of the energies and is given by

\[
\text{GAM}(I,J) = \frac{\text{CMAX}}{(\text{E}(J) \cdot \text{E}(I))^{0.5}}
\]

If the signals \( [\text{SMIC}(I,L)] \) and \( [\text{SMIC}(J,L)] \) are identical in shape but of different amplitudes the \( \text{GAM}(I,J) \) will be equal to 1. If there shapes are significantly different the value of \( \text{GAM}(I,J) \) will be approximately zero. In this way the normalized correlation coefficient provides a measure of similarity of the two signals tested.

4. Determination of the Rough Time Differences between Signals I and L. The raw time difference represents the time difference between the signals in the windows. To obtain the rough time differences between microphone signals
the raw time difference $\tau(I,L)$ must be adjusted by the starting times of the windows as follows

$$R\tau(I,L) = \text{FLOAT}[T(I) - IT(L)] + \tau(I,L)$$

These rough time differences $\tau(I,L) \, I=1,2,\ldots,\text{NMIC}$, and $L=1,[I+1],\ldots,\text{NMIC}$ are part of the input to the least square adjustment section.

E. Determination of Least Square Time Fit

The rough time difference $R\tau(I,J)$ and normalized correlation coefficient $G\alpha(I,J) \, I=1,2,\ldots,\text{NMIC}$, $J=1,2,\ldots,\text{NMIC}$ are now used to obtain a consistent set of time differences by using a weighted least squares procedure. Each step in the procedure is described in the following paragraphs.

1. Establishment of Weights for Least Square Time Fit. A weight is attached to each one of the rough time differences indicating a measure of reliability of those estimates. The measure or weight $G(I,J)$ assigned to $R\tau(I,J)$ is defined to be a function of the normalized correlation coefficient $G\alpha(I,J)$. Different functional relationships have been played with, but at present no way of favoring one over the others has been established. The program in the present form uses the following weighting.

$$G(I,J) = \begin{cases} (G\alpha(I,J))^2 & \text{if } G\alpha(I,J) < 0.5 \\ (G\alpha(I,J))^{1/2} & \text{if } G\alpha(I,J) > 0.5 \end{cases}$$

This attaches slightly more influence to time difference values that have a normalized correlation coefficient greater than 0.5 over those that have correlations less than 0.5.

2. Determination of Least Square Time Fit with MIC 1 as a Reference.

The weights $G(I,J)$ described above are used to define a measure of performance $e$ given by

$$e = \sum_{I=1}^{\text{NMIC}} \sum_{J=1}^{\text{NMIC}} G(I,J) \left( R\tau(I,J) - (\text{TIME}(I) - \text{TIME}(J)) \right)^2$$
The objective is to find the times $\text{TIME}(I) \ i=1,2,\ldots, \ NMIC$ such that $e$ is minimized. A solution of this problem for $G(I,J)=1$ is given by the Author [3] and requires solving for $n$ microphone signals a set of simultaneous linear equations in $n-1$ unknowns when a given microphone has been selected as a reference. In Appendix C a solution for arbitrary $G(I,J)$ with MIC1 as a reference is presented resulting in the following set of simultaneous equations in $t_i$ where $t_i$ is the relative time of arrival of the $i$th signal.

$$
\begin{bmatrix}
\alpha_2 \\
\alpha_3 \\
\alpha_4 \\
\alpha_5 \\
\alpha_6
\end{bmatrix}
= 
\begin{bmatrix}
G(1,1) & G(2,3) & G(2,4) & G(2,5) & G(2,6) \\
G(2,3) & G(2,2) & G(3,4) & G(3,5) & G(3,6) \\
G(2,4) & G(3,4) & G(3,3) & G(4,5) & G(4,6) \\
G(2,5) & G(3,5) & G(4,5) & G(4,4) & G(5,6) \\
G(2,6) & G(3,6) & G(4,6) & G(5,6) & G(6,6)
\end{bmatrix}
\begin{bmatrix}
t_1 \\
t_2 \\
t_3 \\
t_4 \\
t_5
\end{bmatrix}
$$

where

$$
G(1,1)=-(G(1,2)+G(2,3)+G(2,4)+G(2,5)+G(2,6))
$$

$$
G(2,2)=-(G(1,3)+G(2,3)+G(3,4)+G(3,5)+G(3,6))
$$

$$
G(3,3)=-(G(1,4)+G(2,4)+G(3,4)+G(4,5)+G(4,6))
$$

$$
G(4,4)=-(G(1,5)+G(2,5)+G(3,5)+G(4,5)+G(5,6))
$$

$$
G(5,5)=-(G(1,6)+G(2,6)+G(3,6)+G(4,6)+G(5,6))
$$

and

$$
\alpha_2 = - G(1,2)R(1,2)+G(2,3)R(2,3)+G(2,4)R(2,4)+G(2,5)R(2,5)+G(2,6)R(2,6)
$$

$$
\alpha_3 = - G(1,3)R(1,3)-G(2,3)R(2,3)+G(3,4)R(3,4)+G(3,5)R(3,5)+G(3,6)R(3,6)
$$

$$
\alpha_4 = - G(1,4)R(1,4)-G(2,4)R(2,4)-G(3,4)R(3,4)+G(4,5)R(4,5)+G(4,6)R(4,6)
$$

$$
\alpha_5 = - G(1,5)R(1,5)-G(2,5)R(2,5)-G(3,5)R(3,5)-G(4,5)R(4,5)+G(5,6)R(5,6)
$$

$$
\alpha_6 = - G(1,6)R(1,6)-G(2,6)R(2,6)-G(3,6)R(3,6)-G(4,6)R(4,6)-G(5,6)R(5,6)
$$

with

$$
R(I,J) = RTAU(I,J)
$$
This set of equations was solved by using the CJR subroutine package from the 1108 Large Scale Systems Math Pack which is fully described in [5]. The subroutine is accessed with the following call:

```
CALL CJR(A, 6, 5, 6, $400, JC, V)
```

where

- \( a \) = augmented coefficient matrix
- \( b \) = maximum number of columns in A
- \( c \) = maximum number of rows in A
- \( d \) = the number of rows in A
- \( e \) = the number of columns in A
- \( f \) = statement number control is returned if an overflow is detected
- \( g \) = control array
- \( h \) = on input \( V(1) \) is the option indicator, which to solve equations is 4,
  on output \( V(2) \) contains the value of the natural log of the absolute value of the determinant and \( V(1) \) contains the sign of the determinant

On output the last column of A is the solution vector \([t_2, t_3, \ldots, t_6]\) and is called \( AT(2), AT(3), \ldots, AT(6) \). Since microphone 1 was defined to be the reference, \( AT(1) \) is set equal to zero. The \( AT[I] \) represents the starting time for the signal in the Ith window relative to the signal in window 1.

3. Adjustment of Time Differences. Using the \( AT \) vector, a raw corrected time difference can be found by the difference of the components

\[
\text{TAU}(I,J) = AT(I) - AT(J) \quad i=1,2,\ldots,6 \quad j=1,2,\ldots,6
\]

The least square corrected time difference in milliseconds can then be formed by

\[
\text{CTAU}(I,J) = \text{TAU}(I,J) + \text{FLOAT}[IT(I) - IT(J)]
\]

4. Selection of MIC to be used as reference. To select a microphone as a reference for determining the relative times for the position estimator requires
a specification of a performance criterion. We would like to select the MIC as reference that gives the best possible relative times for the position estimator. Upon examining data, it was found that position estimates were sensitive to the selection of a MIC reference even though a least squares procedure had been performed on the time differences. No direct relationship was established however and the following procedure represents a reasonable way to select the reference with no sense of optimality implied. As the normalized correlation coefficient is a measure of reliability of the time differences determined, the sum of the correlation coefficients for all time differences associated with a particular microphone represents a measure of reliability of the time differences for that microphone. This measure was called CMEAS(I) \( I=1,2,\ldots,6 \) and given by

\[
CMEAS(I) = \sum_{J=1}^{6} G(I,J)_{J \neq I}
\]

The value \( K \) for which \( CMEAS(K)_{K=1,2,\ldots,6} \) is a maximum is called KMAX and represents the number of the microphone to be used as a reference. In the output of the times for the position estimator the reference microphone is identified by having the time 0.000.

5. Determination of Relative Times for the Position Estimator. The position estimator USRAN[1] requires six relative arrival times and the proper meteorological data as input to determine the position of the source. The number (KMAX) of the microphone signal that was selected as a reference was determined previously. To find the times relative to this microphone could be easily accomplished by filling out the lower triangular part of the CTAU(I,L) array with the negative of upper triangular part. In this way the time differences with respect to each microphone appear on the rows of CTAU(I,L) and the selection of the KMAX microphone corresponds to selecting a row.
F. Printing the Output

An example of the overall program output format is given in Figure 3 and consists of the four basic parts described below.

1. Shot Information. The header information is in reference to the data files from the PASS experiment and gives the day, time, and position of the shot as well as the position number, starting times and lengths (MSEC) of the data record for the microphones recording.

2. Window Information. The window starting time in MSEC determined by the program relative to the starting times for each microphone record are given along with the signal energy within the window. The microphones numbered 1 through 6 correspond to the normal ordering of the PASS microphone numbers. The window signal energy and starting time could be used in an interactive mode (not programmed at this time) to allow the operator to check if a signal appears in the window or not.

3. Time Differences Information. The normalized correlation coefficient, time differences in MSEC, and corrected time differences in seconds are given for each pair of microphone signals. These results may be used to infer the overall reliability provided by the normalized correlation coefficient and a measure of consistency by examining the changes made in the rough time differences RTAU(I,J) to get the corrected time differences.

4. Met and Timing for Position Estimator. The times in seconds and the Met information that could be used as input to a position estimator are provided for interfacing purposes. The timing information appears in an array TIME(J) J=1,2,...,6 while the temperature, wind direction and wind speed are labeled TEMP, MILS, and KNOTS respectively.

III. USING THE PROGRAM

The procedure given in this section will apply to the use of the program on the WSMR UNIVAC 1108 system. Presently the program is stored under file
Figure 3. Example of the program output format

Day 311; Burst Time 010,993, 1159 SLC
Subsection: 19 MICs

The Starting Times for Each Microphone Signal

MIC 1: 010 BRS 14,771 SEC
MIC 2: 010 BRS 14,771 SEC
MIC 3: 010 BRS 14,771 SEC
MIC 4: 010 BRS 14,771 SEC
MIC 5: 010 BRS 14,771 SEC
MIC 6: 010 BRS 14,771 SEC

The Window Starting Times (sec) Relative to Above

MIC 1  MIC 2  MIC 3  MIC 4  MIC 5  MIC 6
010   010   010   010   010   010

The Signal Energy Within Each Window

MIC 1  MIC 2  MIC 3  MIC 4  MIC 5  MIC 6
1431.79  349.60  4322.27  211.2378  35412347  34291798

The Correlation, Time Differences (sec), and Corrected Time Differences (sec) Between Each Pair of Microphone Signals

| GAMMA(1,2) | GAMMA(1,3) | GAMMA(1,4) | GAMMA(1,5) | GAMMA(1,6) | GAMMA(2,3) | GAMMA(2,4) | GAMMA(2,5) | GAMMA(2,6) | GAMMA(3,4) | GAMMA(3,5) | GAMMA(3,6) | GAMMA(4,5) | GAMMA(4,6) | GAMMA(5,6) | CTAU(1,2) | CTAU(1,3) | CTAU(1,4) | CTAU(1,5) | CTAU(1,6) | CTAU(2,3) | CTAU(2,4) | CTAU(2,5) | CTAU(2,6) | CTAU(3,4) | CTAU(3,5) | CTAU(3,6) | CTAU(4,5) | CTAU(4,6) | CTAU(5,6) |
|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|
| 4.93      | 7.02      | 2.03      | 7.03      | 7.23      | 7.02      | 7.02      | 7.24      | 7.02      | 7.02      | 7.02      | 7.02      | 7.02      | 7.02      | 7.02      | 7.02      | 7.02      | 7.02      | 7.02      | 7.02      | 7.02      | 7.02      | 7.02      | 7.02      | 7.02      | 7.02      | 7.02      | 7.02      | 7.02      | 7.02      | 7.02      |

The Time in SEC to be Used for Input to a Position Estimator

<table>
<thead>
<tr>
<th>TIME(1)</th>
<th>TIME(2)</th>
<th>TIME(3)</th>
<th>TIME(4)</th>
<th>TIME(5)</th>
<th>TIME(6)</th>
</tr>
</thead>
<tbody>
<tr>
<td>-4.319</td>
<td>-4.319</td>
<td>-4.319</td>
<td>-4.319</td>
<td>-4.319</td>
<td>-4.319</td>
</tr>
</tbody>
</table>

The Set to a Microphone as Input to Position Estimator

TEMPS: 34 DEG C.
WIND DIRECTION: 6180 MILS
WIND SPEED: 9 KNOTS

Figure 3. Example of the program output format
name and element LCLPF.SOUNDR in both a symbolic and absolute form. The following control statements will execute the program:

@ASC, AZ S3-D341-MB-1. Assign data file to run
@USE 12., S3-D341-MB-1 Use file S3-D341-MB-1 as logical unit 12
@XQT LCLPF.SOUNDR Execute program.

If the program is to be executed on another computer a duplicate of the symbolic form of SOUNDR must be obtained and if a different data structure is to be used the subroutine RDATA must be rewritten. The main program and subroutine can then be compiled on the computer to be used.

IV. RESULTS

The program LCLPF.SOUNDR was run using various signals from the PASS experiment as input. The results for the test shots given in Table 2 are shown in Figures 4 through 10. The times and Met data indicated in Figures 4 through 10 were used in a position estimator program resulting in the Miss distances given in Table 3.

<table>
<thead>
<tr>
<th>UNIVAC 1108 File No.</th>
<th>Source</th>
<th>Day</th>
<th>MIC Array</th>
<th>Identification Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1-D341-MB-1.</td>
<td>1</td>
<td>341</td>
<td>B</td>
<td>1</td>
</tr>
<tr>
<td>S1-D341-MB-2.</td>
<td>1</td>
<td>341</td>
<td>B</td>
<td>2</td>
</tr>
<tr>
<td>S2-D341-MB-1.</td>
<td>2</td>
<td>341</td>
<td>B</td>
<td>1</td>
</tr>
<tr>
<td>S2-D341-MB-2.</td>
<td>2</td>
<td>341</td>
<td>B</td>
<td>2</td>
</tr>
<tr>
<td>S2-D341-MB-4.</td>
<td>2</td>
<td>341</td>
<td>B</td>
<td>4</td>
</tr>
<tr>
<td>S3-D341-MB-2.</td>
<td>3</td>
<td>341</td>
<td>B</td>
<td>2</td>
</tr>
<tr>
<td>S7-D341-MB-2.</td>
<td>7</td>
<td>341</td>
<td>B</td>
<td>2</td>
</tr>
</tbody>
</table>
DAY 341: SHOT TIME 5:16 HRS 2.074 SEC
SOURCE 1 MILK ARRAY B
MIC: 27, 29, 30, 31, 32, 1920 TIMES/MIC

THE STARTING TIMES FOR EACH MICROPHONE SIGNAL
MIC(1): 5:16 HRS 35,411 SEC
MIC(2): 5:16 HRS 36,502 SEC
MIC(3): 5:16 HRS 41,499 SEC
MIC(4): 5:16 HRS 43,005 SEC

THE WINDOW STARTING TIMES (SECONDS) RELATIVE TO ABOVE
MIC 1  MIC 2  MIC 3  MIC 4  MIC 5  MIC 6
808  603  658  /16  701  747

THE SIGNAL ENERGY WITHIN EACH WINDOW
MIC 1  MIC 2  MIC 3  MIC 4  MIC 5  MIC 6
3622710, 2073226, 9752810, 26270444, 11659675, 1395643

THE CORRELATION TIMES DIFFERENCE (SECONDS) AND CORRECTED TIME DIFFERENCE (SECONDS)
BETWEEN EACH PAIR OF MICROPHONE SIGNALS
GAMMA(1,2) = 0.559  GAMMA(1,3) = 0.725  GAMMA(1,4) = 0.171  GAMMA(1,5) = 0.478  GAMMA(1,6) = 0.534  GAMMA(2,3) = 0.395  GAMMA(2,4) = 0.412  GAMMA(2,5) = 0.336  GAMMA(2,6) = 0.425  GAMMA(3,4) = 0.421  GAMMA(3,5) = 0.370  GAMMA(3,6) = 0.457  GAMMA(4,5) = 0.422  GAMMA(4,6) = 0.439  GAMMA(5,6) = 0.376
RIAN(1,2) = -584.0  RIAN(1,3) = -291.0  RIAN(1,4) = -384.0  RIAN(1,5) = -507.0  RIAN(1,6) = -510.0  RIAN(2,3) = -129.0  RIAN(2,4) = -297.0  RIAN(2,5) = -492.0  RIAN(2,6) = -734.0  RIAN(3,4) = -157.0  RIAN(3,5) = -369.0  RIAN(3,6) = -604.0  RIAN(4,5) = -201.0  RIAN(4,6) = -435.0  RIAN(5,6) = -230.0
CTAU(1,2) = -864.0  CTAU(1,3) = -2101.0  CTAU(1,4) = -3860.0  CTAU(1,5) = -5070.0  CTAU(1,6) = -5100.0  CTAU(2,3) = -1295.0  CTAU(2,4) = -2975.0  CTAU(2,5) = -4925.0  CTAU(2,6) = -7345.0  CTAU(3,4) = -1570.0  CTAU(3,5) = -3690.0  CTAU(3,6) = -6040.0  CTAU(4,5) = -2010.0  CTAU(4,6) = -4350.0  CTAU(5,6) = -2300.0

THE TIMES IN SEC TO BE USED FOR INPUT TO A POSITION ESTIMATOR
TIME(1) = 2.070 SEC
TIME(2) = 0.084 SEC
TIME(3) = 3.182 SEC
TIME(4) = 3.061 SEC
TIME(5) = 5.883 SEC
TIME(6) = 8.216 SEC

THE RL TO A BE USED AS INPUT TO POSITION ESTIMATOR
TEMP = 6.7 DEG C
WIND DIRECTION = 6380 MILS
WIND SPEED = 9 KNOTS

Figure 4. Results from PASS shot Sl-D341-MB-1.
Figure 5. Results from PASS shot S1-D341-MB-2.
Figure 6. Results from PASS shot S2-D341-MB-1.
Figure 7. Results from PASS shot S2-D341-MB-2.
| Day | Shot Time | Time Sync | 1.7 SEC
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>MIC 1</td>
<td>MIC 2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>MIC 3</td>
<td>MIC 4</td>
</tr>
<tr>
<td></td>
<td></td>
<td>MIC 5</td>
<td>MIC 6</td>
</tr>
</tbody>
</table>

**The Starting Times for Each Microphone Signal**

- MIC(21): 01:15 HRS 31.644 SEC
- MIC(22): 01:15 HRS 34.644 SEC
- MIC(23): 01:15 HRS 35.345 SEC

**The Window Starting Time Stages Relative to Above**

<table>
<thead>
<tr>
<th>MIC 1</th>
<th>MIC 2</th>
<th>MIC 3</th>
<th>MIC 4</th>
<th>MIC 5</th>
<th>MIC 6</th>
</tr>
</thead>
<tbody>
<tr>
<td>754</td>
<td>762</td>
<td>950</td>
<td>804</td>
<td>717</td>
<td></td>
</tr>
</tbody>
</table>

**The Signal Energy Within Each Window**

<table>
<thead>
<tr>
<th>MIC 1</th>
<th>MIC 2</th>
<th>MIC 3</th>
<th>MIC 4</th>
<th>MIC 5</th>
<th>MIC 6</th>
</tr>
</thead>
<tbody>
<tr>
<td>249/20</td>
<td>31231</td>
<td>405041</td>
<td>619627</td>
<td>2354578</td>
<td>598184</td>
</tr>
</tbody>
</table>

**The Correlation, Time Differences (mSec), and Corrected Time Differences (sec) Between Each Pair of Microphone Signals**

<p>| | | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>R1A(1+2)</td>
<td>-1.144</td>
<td>R1A(1+3)</td>
<td>-0.144</td>
<td>R1A(1+4)</td>
<td>-0.144</td>
</tr>
</tbody>
</table>

**The Times in SEC to be Used for Input to a Position Estimator**

| TIME(1) | -2.641 SEC |
| TIME(2) | -2.641 SEC |
| TIME(3) | -2.641 SEC |
| TIME(4) | -1.132 SEC |
| TIME(5) | 0.000 SEC  |
| TIME(6) | 1.722 SEC  |

**The Alt to be Used as Input to Position Estimator**

- TEMP: 2.6 DEGS C.
- WIND DIRECTION: 6500 MILES
- WIND SPEED: 8 KNOTS

Figure 8. Results from PASS shot S2-D341-MB-4.
THE WINDOW STARTING TIMES (BASED ON RELATIVE TO ABOVE)

<table>
<thead>
<tr>
<th>MIC 1</th>
<th>MIC 2</th>
<th>MIC 3</th>
<th>MIC 4</th>
<th>MIC 5</th>
<th>MIC 6</th>
</tr>
</thead>
<tbody>
<tr>
<td>5933733</td>
<td>300650</td>
<td>4848166</td>
<td>19053956</td>
<td>37294450</td>
<td>25889576</td>
</tr>
</tbody>
</table>

THE CORRELATION TIME DIFFERENCES (MICSEC) AND CORRECTED TIME DIFFERENCES (SEC) BETWEEN EACH PAIR OF MICROPHONE SIGNALS

<table>
<thead>
<tr>
<th>GAMMA(1-2)</th>
<th>GAMMA(1-3)</th>
<th>GAMMA(1-4)</th>
<th>GAMMA(1-5)</th>
<th>GAMMA(1-6)</th>
<th>GAMMA(2-3)</th>
<th>GAMMA(2-4)</th>
<th>GAMMA(2-5)</th>
<th>GAMMA(2-6)</th>
<th>GAMMA(3-4)</th>
<th>GAMMA(3-5)</th>
<th>GAMMA(3-6)</th>
<th>GAMMA(4-5)</th>
<th>GAMMA(4-6)</th>
<th>GAMMA(5-6)</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>RMAU(1-2)</th>
<th>RMAU(1-3)</th>
<th>RMAU(1-4)</th>
<th>RMAU(1-5)</th>
<th>RMAU(1-6)</th>
<th>RMAU(2-3)</th>
<th>RMAU(2-4)</th>
<th>RMAU(2-5)</th>
<th>RMAU(2-6)</th>
<th>RMAU(3-4)</th>
<th>RMAU(3-5)</th>
<th>RMAU(3-6)</th>
<th>RMAU(4-5)</th>
<th>RMAU(4-6)</th>
<th>RMAU(5-6)</th>
</tr>
</thead>
<tbody>
<tr>
<td>700.0</td>
<td>100.0</td>
<td>123.0</td>
<td>1031.0</td>
<td>117.0</td>
<td>497.0</td>
<td>948.0</td>
<td>123.0</td>
<td>-786.0</td>
<td>22.0</td>
<td>-375.0</td>
<td>-130.0</td>
<td>-397.0</td>
<td>-1302.0</td>
<td>-936.0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>CMAU(1-2)</th>
<th>CMAU(1-3)</th>
<th>CMAU(1-4)</th>
<th>CMAU(1-5)</th>
<th>CMAU(1-6)</th>
<th>CMAU(2-3)</th>
<th>CMAU(2-4)</th>
<th>CMAU(2-5)</th>
<th>CMAU(2-6)</th>
<th>CMAU(3-4)</th>
<th>CMAU(3-5)</th>
<th>CMAU(3-6)</th>
<th>CMAU(4-5)</th>
<th>CMAU(4-6)</th>
<th>CMAU(5-6)</th>
</tr>
</thead>
<tbody>
<tr>
<td>902.0</td>
<td>1400.0</td>
<td>1233.0</td>
<td>1033.0</td>
<td>115.0</td>
<td>499.0</td>
<td>952.0</td>
<td>123.0</td>
<td>-787.0</td>
<td>22.0</td>
<td>-376.0</td>
<td>-130.0</td>
<td>-397.0</td>
<td>-1302.0</td>
<td>-936.0</td>
</tr>
</tbody>
</table>

THE TIMES IN SEC TO BE USED FOR INPUT TO A POSITION ESTIMATOR

<table>
<thead>
<tr>
<th>TIME(1)</th>
<th>TIME(2)</th>
<th>TIME(3)</th>
<th>TIME(4)</th>
<th>TIME(5)</th>
<th>TIME(6)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.033</td>
<td>1.131</td>
<td>-1.340</td>
<td>-1.395</td>
<td>-0.000</td>
<td>-0.118</td>
</tr>
</tbody>
</table>

THE ALT TO A PL USED AS INPUT TO POSITION ESTIMATOR

<table>
<thead>
<tr>
<th>ATMP</th>
<th>WIND DIRECTION</th>
<th>WIND SPEED</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.4 DEG.</td>
<td>6100 MILS</td>
<td>9 KNOTS</td>
</tr>
</tbody>
</table>

Figure 9. Results from PASS shot S3-D341-MB-2.
Figure 10. Results from PASS shot S7-D341-MB-2.
Table 3. Miss Distances for PASS Data Examples

<table>
<thead>
<tr>
<th>File No.</th>
<th>Fig. No.</th>
<th>Miss Distance (Meters)</th>
<th>Distance to Center of Array (Meters)</th>
<th>Ratio of Miss Distance to Total Distance</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1-D341-MB-1.</td>
<td>4</td>
<td>430.0</td>
<td>12,678.5</td>
<td>.034</td>
</tr>
<tr>
<td>S1-D341-MB-2.</td>
<td>5</td>
<td>195.5</td>
<td>12,678.5</td>
<td>.015</td>
</tr>
<tr>
<td>S2-D341-MB-1.</td>
<td>5</td>
<td>176.4</td>
<td>11,784.8</td>
<td>.015</td>
</tr>
<tr>
<td>S2-D341-MB-2</td>
<td>7</td>
<td>192.8</td>
<td>11,784.8</td>
<td>.016</td>
</tr>
<tr>
<td>S2-D341-MB-4</td>
<td>8</td>
<td>1015.2</td>
<td>11,784.8</td>
<td>.086</td>
</tr>
<tr>
<td>S3-D341-MB-2</td>
<td>9</td>
<td>395.54</td>
<td>11,471.9</td>
<td>.034</td>
</tr>
<tr>
<td>S7-D341-MB-2</td>
<td>10</td>
<td>291.8</td>
<td>16,900.7</td>
<td>.017</td>
</tr>
</tbody>
</table>
V. CONCLUSIONS

The present edition of the "Time Difference Estimator Program" has been presented in the first three sections of this report and the results from its application to a number of arbitrarily selected signals from the PASS experiment was given in the fourth section. The results show good time duration estimates, based on the concept of miss distance; however, one should realize that with only seven samples not much can be said of the program's statistical performance other than it is looking very promising.

From Table 2 and Figures 4-10 it is seen that the program satisfactorily determined relative times such that target position could be estimated with miss distances around two hundred meters for targets of about twelve kilometers in range. It appears that as one would intuitively expect, correlation coefficients much lower than 0.5 for the time differences, Figure 4 and Figure 8, result in the considerable sized miss distances given in Table 2.

The application of the program to existing data has pointed out need for further research into several areas in order to improve the procedure.

(1) In order to eliminate inaccurate data a threshold value for the correlation coefficient must be determined for which the associated time difference estimates with less than that threshold are claimed unreliable and discarded.

(2) A procedure should be developed to assign realistic weights for use in the least squares procedure perhaps as a function of the normalized correlation coefficient.

(3) The overall effectiveness of the procedure should be established by providing the variance or a bound on the variances of the time
difference estimates. This will require a theoretical development along with an examination of a large amount of data for experimental verification.

(4) The program should be altered to present a workable procedure for handling the multiple target problem.
APPENDIX A

Time Differences Estimator Program Listing

```
11C  THE DIFFERENCES ESTIMATOR PROGRAM
12C
13C GLOSSARY OF VARIABLES:
14C
15C AN/MICROPHONES
16C N1 = NUMBER OF DATA POINTS FOR EACH MICROPHONE
17C N2 = NUMBER OF POINTS IN SLIDING WINDOW
18C N3 = NUMBER OF POINTS IN THE FOURIER WINDOW
19C N4 = SIGNAL AMPLITUDE FOR MIC J AT TIME T RELATIVE TO T0(t)
20C T0(t) = STARTING TIME FOR MICROPHONE J IN RELATION TO TIME 0(t)
21C T0J(t) = TRUE STARTING POINT FOR MICROPHONE J RELATIVE TO T0(t)
22C T0J(t) = TRUE START TIME FOR FOURIER WINDOW IN RELATION TO T0(t)
23C E(j,t) = ENERGY WITHIN CORRELATION WINDOW FOR SIGNAL J
24C DELTAJ = TIME DIFFERENCE BETWEEN MICROPHONE SIGNALS AT T
25C SIGMAJ = FOURTH DEGREES C DIRECT OR CORRELATION 20
26C DISTRI = DISTANCE BETWEEN MICROPHONE STATIONS 20
27C
28C N1 = NUMBER OF MICROPHONES
29C N2 = NUMBER OF DATA POINTS FOR EACH MICROPHONE
30C N3 = NUMBER OF POINTS IN SLIDING WINDOW
31C N4 = NUMBER OF POINTS IN THE FOURIER WINDOW
32C SIGMAJ = FOURTH DEGREES C DIRECT OR CORRELATION 20
33C DISTRI = DISTANCE BETWEEN MICROPHONE STATIONS 20
```
32

INITIALIZING

DIMENSION LMAP(6)*IMHR(6)*IMIN(6)*SEC(6)*MIC(6)*TIME(6)

DIMENSION IMOP(6)*IMIN(6)*MIC(6)*TIME(6)*IMIN(6)*MIC(6)*TIME(6)

DIMENSION SEC(6)*MIC(6)*TIME(6)*IMIN(6)*MIC(6)*TIME(6)

COMPLEX X(1024),Y(1024),WIM(1024),XY(1024),YY(1024)

REAL 5

REAL 192

REAL 342

REAL 512

BRINGING IN DATA FROM MASTER FILE

CALL NAME(SMIL*MIC*LMAP*IMIN*SEC*TEM*HILS*LAND10)

DO 50 I=1:MIC

IFC=SEC(I)*10000

IT(I)=IMIN(I)*10*1000*10*1000*1000

50 CONTINUE

COMPUTATION OF MOON ARRIVAL TIMES

DO 90 J=1:MIC

I=0.0

LMAX=0.0

DO 95 K=1:NSW

IFM=MIC(J)+MIC(J+K)

TE=TIM(I)+IFM

QK=QJ(I)

QJ(I)=QJ(I)+1

95 CONTINUE

IFM=0.0

IFM=0.0

CONTINUE

QJ(I)=QJ(I)+1

90 CONTINUE

COMPUTATION OF WINDOW STARTING POINTS

DO 105 I=1:MIC

NSW-NSW/4

MODE=MODE(1)+MODE

105 IF(MODE.GT.I6) GO TO 105

106 GO TO 110

106 CONTINUE

110 CONTINUE

111 MODE-MIC

112 IF(MODE.GT.I6) GO TO 106

113 MODE=1

114 IF(MODE.GT.I6) GO TO 110

114 CONTINUE
I0: \textsc{printing the window starting lines}
100: \textsc{write(6,2014)}
101: \textsc{write(6,2014)}
102: \textsc{write(6,2014)}
103: \textsc{write(6,2014)}
104: \textsc{write(6,2014)}
105: \textsc{write(6,2014)}
106: \textsc{write(6,2014)}
107: \textsc{write(6,2014)}
108: \textsc{write(6,2014)}
109: \textsc{write(6,2014)}
110: \textsc{write(6,2014)}
111: \textsc{write(6,2014)}
112: \textsc{write(6,2014)}
113: \textsc{write(6,2014)}
114: \textsc{write(6,2014)}
115: \textsc{write(6,2014)}
116: \textsc{write(6,2014)}
117: \textsc{write(6,2014)}
118: \textsc{write(6,2014)}
119: \textsc{write(6,2014)}
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121: \textsc{write(6,2014)}
122: \textsc{write(6,2014)}
123: \textsc{write(6,2014)}
124: \textsc{write(6,2014)}
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134: \textsc{write(6,2014)}
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136: \textsc{write(6,2014)}
137: \textsc{write(6,2014)}
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140: \textsc{write(6,2014)}
141: \textsc{write(6,2014)}
142: \textsc{write(6,2014)}
143: \textsc{write(6,2014)}
144: \textsc{write(6,2014)}
145: \textsc{write(6,2014)}
146: \textsc{write(6,2014)}
147: \textsc{write(6,2014)}
148: \textsc{write(6,2014)}
149: \textsc{write(6,2014)}
150: \textsc{write(6,2014)}
151: \textsc{write(6,2014)}
152: \textsc{write(6,2014)}
153: \textsc{write(6,2014)}
154: \textsc{write(6,2014)}
155: \textsc{write(6,2014)}
156: \textsc{write(6,2014)}
157: \textsc{write(6,2014)}
158: \textsc{write(6,2014)}
159: \textsc{write(6,2014)}
160: \textsc{write(6,2014)}
161: \textsc{write(6,2014)}
162: \textsc{write(6,2014)}
163: \textsc{write(6,2014)}
164: \textsc{write(6,2014)}
165: \textsc{write(6,2014)}
166: \textsc{write(6,2014)}
167: \textsc{write(6,2014)}
168: \textsc{write(6,2014)}
169: \textsc{write(6,2014)}
170: \textsc{write(6,2014)}
171: \textsc{write(6,2014)}
172: \textsc{write(6,2014)}
173: \textsc{write(6,2014)}
174: \textsc{write(6,2014)}
175: \textsc{write(6,2014)}
176: \textsc{write(6,2014)}
177: \textsc{write(6,2014)}
178: \textsc{write(6,2014)}
179: \textsc{write(6,2014)}
180: \textsc{write(6,2014)}
1807  XX(I) = (XX(I) + Y(I) * Y(I)) / 2
1817  YY(I) = YY(I) + XX(I)
1827  IF (XX(I) < 1.0) THEN 710
1837  XX(I) = XX(I) * 1024
1847  YY(I) = YY(I) * 1024
1857  CONTINUE

1907  CALL FOUR(XX,1024,1,WORK)
1917  GO TO 125
1927  ZZ(I) = CONJG(XX(I))
1937  ZZ(I) = ZZ(I) + ZZ(I)
1947  YY(I) = YY(I) * ZZ(I)
1957  YY(I) = YY(I) / 2

2007  CALL FOUR(XX,1024,2,WORK)
2017  ZZ(I) = YY(I)
2027  YY(I) = YY(I) * ZZ(I)
2037  ZZ(I) = ZZ(I) * ZZ(I)
2047  XX(I) = XX(I) * ZZ(I)
2057  XX(I) = XX(I) / 2

2107  COMPUTATION OF FREQUENCY FILTER VALUES
2117  FA = REAL(XX(I))
2127  FR = YY(I)
2137  GO TO 716
2147  CONTINUE
2157  PRE = PRE / PRA
2167  IF (PRE > 1.0) THEN 719
2177  PRE = PRE + PRA
2187  GO TO 721
2197  CONTINUE
2207  Z(I) = CONJG(PREF)
2217  YY(I) = YY(I) * Z(I)
2227  YY(I) = YY(I) * Z(I)
2237  YY(I) = YY(I) * Z(I)
2247  PRE = 0.0
2257  CONTINUE
2267  APPLICATION OF FREQUENCY FILTER
2277  YY(I) = YY(I) * Z(I)
2287  YY(I) = YY(I) * Z(I)
APPLICATION OF COMB FILTER FOR 60 CYCLE AND HARMONICS
2410C

2411C: 13. CONTINUE
2412C: DATA COMBK(1,•10,63/121,126,183,3165,244,249/)
2413C: MX MODEMX(I)
2414C: IF (DX,L.L,0) GO TO 131
2415C: Y(I)=Y(I)*0.0,0,0)
2416C: 131 DO 133 N=2,10+2
2417C: MX=MODEMX(N)
2418C: IF (NX,L.L,0) GO TO 138
2419C: MX-MODEMX(41)
2511C: DO 132 L=NX,MY
2512C: Y(I)=Y(I)*0.0,0,0)
2513C: MX-MODEMX(L)
2514C: Y(MAX)=Y(I)*0.0,0,0)
2515C: 132 CONTINUE
2516C: 133 CONTINUE
2517C: 138 CONTINUE
2518C:
2519C: FINDING THE RAW TIME DIFFERENCES BETWEEN THE WINDOWED SIGNALS
2610C
2611C: CALL FOURG(Y,1024+1,WORK)
2612C: CMAX=0.
2613C: TMAX=O.
2614C: DO 140 L=1,1024
2615C: CA-REAL(Y(I))
2616C: GA-REAL(Y)
2617C: IF (CA.LE.CMAX) GO TO 140
2618C: CMAX=CA
2619C: TMAX=L
2620C: 140 CONTINUE
2621C: TAU(I,J)=TMAX-MPW-1
2710C:
2711C: DETERMINATION OF THE NORMALIZED CORRELATION COEFFICIENT
2712C
2713C: G(I,J)=CMAX/(CE.IKE(1)*0.5)
2714C: GA=REAL(I/J)
2715C: 150 CONTINUE
2716C: 200 CONTINUE
2717C:
2718C: DETERMINATION OF ROUGH TIME DIFFERENCES BETWEEN SIGNALS 1 AND 2
2810C
2811C: WRITE(6,2016)
2812C: WRITE(6,2017)
2813C: 2017 FORMAT(* BETWEEN EACH PAIR OF MICROPHONE SIGNALS*)
2814C: DO 250 I=1,5
2815C: MX=+1
2816C: DO 240 L=NX-MX
2817C: RTAU(I,L)=FLOAT(TT(I)+1L)*TAU(I,L)
2818C: 2016 FORMAT(* THE CORRELATION, TIME DIFFERENCES(MSEC) AND CORRECTED
2819C: TIME DIFFERENCES(SEC) *)
2820C: 240 CONTINUE
2821C: 250 CONTINUE
2910C:
2911C: SELECTION OF MIC TO BE USED AS REFERENCE
2912C
2913C: CMAS(1)=01,1+6G(1+13461+19,91,5)M+1,6)
2914C: CMAS(2)=01,1+146(1+13461+19,91,5)M(246
2915C: CMAS(3)=01,1+146(1+13461+19,91,5)M(3146)
2916C: CMAS(4)=01,1+146(1+13461+19,91,5)M(46)
36

361:  A(I,I) = G(I,1) + G(I,2) + G(I,3) + G(I,4) + G(I,5) + G(I,6)
362:  A(I,2) = G(2,1) + G(2,2) + G(2,3) + G(2,4) + G(2,5) + G(2,6)
363:  A(I,3) = G(3,1) + G(3,2) + G(3,3) + G(3,4) + G(3,5) + G(3,6)
364:  A(I,4) = G(4,1) + G(4,2) + G(4,3) + G(4,4) + G(4,5) + G(4,6)
365:  A(I,5) = G(5,1) + G(5,2) + G(5,3) + G(5,4) + G(5,5) + G(5,6)
366:  A(I,6) = G(6,1) + G(6,2) + G(6,3) + G(6,4) + G(6,5) + G(6,6)
367:  A(J,I) = TAU(I,1) + TAU(I,2) + TAU(I,3) + TAU(I,4) + TAU(I,5) + TAU(I,6)
368:  A(J,2) = TAU(I,1) + TAU(I,2) + TAU(I,3) + TAU(I,4) + TAU(I,5) + TAU(I,6)
369:  A(J,3) = TAU(I,1) + TAU(I,2) + TAU(I,3) + TAU(I,4) + TAU(I,5) + TAU(I,6)
370:  A(J,4) = TAU(I,1) + TAU(I,2) + TAU(I,3) + TAU(I,4) + TAU(I,5) + TAU(I,6)
371:  A(J,5) = TAU(I,1) + TAU(I,2) + TAU(I,3) + TAU(I,4) + TAU(I,5) + TAU(I,6)
372:  A(J,6) = TAU(I,1) + TAU(I,2) + TAU(I,3) + TAU(I,4) + TAU(I,5) + TAU(I,6)
373:  CALL GJR(A,6,5,5,6,4406,JC,V)
374:  AT(1) = 0.
375:  DO 295 I = 2,6
376:  AT(I) = AT(I-1) + 1
377:  295 CONTINUE
378:  ADJUSTMENT OF TIME REFERENCES
379:  DO 310 I = 1,5
380:  AT(I) = I + 1
381:  310 CONTINUE
382:  I = 1
383:  DO 300 J = 1,5
384:  TAU(I,J) = AT(I) - AT(J)
385:  300 CONTINUE
386:  CALL TAU(I,J) = TAU(I,J) + LOAD(I,I) - TAU(I,J)

387:  ESTABLISHMENT OF WEIGHTS FOR LEAST SQUARE TIME FIT
388:  I = 1
389:  DO 270 J = 1,5
390:  W(I,J) = W(I,J) + AT(I,J)**2
391:  270 CONTINUE
392:  W(I,J) = W(I,J) / SUM(J=1,5, W(I,J))
393:  290 CONTINUE
394:  CALL W(I,J) = W(I,J) / SUM(J=1,5, W(I,J))
395:  CALL AT(I,J) = AT(I,J) / SUM(J=1,5, W(I,J))
396:  END

397:  DETERMINATION OF LEAST SQUARES TIME FIT WITH M(T2) AS REFERENCE
398:  DO 290 I = 1,4
399:  DO 290 J = 1,5
400:  AT(I,J) = AT(1,J) + AT(I,J)
401:  AT(I,J) = AT(I,J) / W(I,J)
402:  290 CONTINUE
403:  CALL AT(I,J) = AT(I,J) / W(I,J)
404:  CALL AT(I,J) = AT(I,J) / W(I,J)
405:  END
CIAU(J) = CIAU(J-1)/1000.

PRINTING CORRECTION FACTORS AND CORRECTED TIME DIFFERENCES

WRITE(6,2001) J, Time(J), JAM(J), P, PMIL(J), LMIL(J), CIAU(J)
2001 FORMAT(2X, 1X, 'TIME(J) ', 1X, 'JAM(J) ', 1X, 'P ', 1X, 'PMIL(J) ', 1X, 'LMIL(J) ', 1X, 'CIAU(J) ', 1X, 'F4.3')

300 CONTINUE
310 CONTINUE

DETERMINATION OF RELATIVE TIMES FOR THE POSITION ESTIMATOR

DO 620 J = 1, 5
620 CIAU(J) = CIAU(J-1)
630 CONTINUE

DO 640 J = 1, 5
640 CIAU(J) = CIAU(J-1, MAX)
650 CONTINUE

PRINTING THE RELATIVE TIMES FOR POSITION ESTIMATOR

WRITE(6, 2005) 2005 FORMAT(// ' THE TIMES IN SEC TO BE USED FOR INPUT TO A POSITION ESTIMATOR' )
500 CIAU = 1, MAX
WRITE(6, 2003) J, TIME(J)
503 CIAU = 1, MAX
WRITE(6, 2025) 2025 FORMAT(//)

OUTPUTTING THE NET INFORMATION

WRITE(6, 2021) 2021 FORMAT(' THE NET TO A BE USED AS INPUT TO POSITION ESTIMATOR' )
WRITE(6, 2022) TEMP
2022 FORMAT(2X, 'TEMP = ' F4.1, ' DEG C.' )
WRITE(6, 2023) MILS
2023 FORMAT(2X, 'MILS')
WRITE(6, 2024) KNOTS
2024 FORMAT(' WIND SPEED = ' F4.1, ' KNOTS')
GO TO 401
400 WRITE(6, 2015)
410 GO TO 401
415 CONTINUE
END
APPENDIX B

Subroutine RDATA Program Listing

SUBROUTINE RDATA

DIMENSION MIC(I),HOR(I),MIN(I),SEC(I),MD,MM,MAIN,TIME
DIMENSION VAL(I)

WRITE(5,10)
WRITE(6,11)
WRITE(7,12)
WRITE(8,13)
WRITE(6,14)
WRITE(6,15)
WRITE(6,16)
WRITE(8,17)
WRITE(9,18)
WRITE(9,19)
WRITE(9,20)
WRITE(10,21)
WRITE(11,22)
WRITE(11,23)
WRITE(11,24)
WRITE(8,25)
WRITE(9,26)
WRITE(11,27)
WRITE(9,28)
WRITE(9,29)
WRITE(8,30)
WRITE(8,31)
WRITE(8,32)
WRITE(8,33)
WRITE(8,34)
WRITE(8,35)
WRITE(8,36)
WRITE(8,37)
WRITE(8,38)
WRITE(8,39)
WRITE(8,40)

END
APPENDIX C

An Estimate of the Noise Power Spectral Density for a PASS Run
APPENDIX D
Derivation of Weighted Least Square Solution

The performance index to be minimized is given by
\[ e = \sum_{i=1}^{N} \sum_{j=1}^{N} \gamma_{ij} [r_{ij} - (t_i - t_j)]^2 \]

In this expression \( r_{ij} \) represents the estimate of the rough time difference between signals from microphone \( i \) and \( j \), \( \gamma_{ij} \) is the weight associated with that estimate, and \( t_i \) is the time of arrival of the signal at microphone \( i \).

If we select \( t_1 = 0 \) as a reference and use six microphones, \( e \) can be written as follows.
\[ e = \gamma_{12} (r_{12} - (-t_2))^2 + \gamma_{13} (r_{13} - (-t_3))^2 + \cdots + \gamma_{16} (r_{16} - (-t_6))^2 \]
\[ + \sum_{i>j}^{6} \sum_{j=1}^{6} \gamma_{ij} [r_{ij} - (t_i - t_j)]^2 \]

A necessary, in this case sufficient because of convexity, condition for \( e \) to be minimized is that
\[ \frac{\partial e}{\partial t_i} = 0 \quad i = 2, 3, \ldots, 6 \]

Taking the partial derivatives of \( e \) we have the following set of simultaneous linear equations in \( t_2, t_3, \ldots, t_6 \) that can be easily solved.

\[
\begin{bmatrix}
\alpha_2 \\
\alpha_3 \\
\alpha_4 \\
\alpha_5 \\
\alpha_6 \\
\end{bmatrix} =
\begin{bmatrix}
\gamma_{22} & \gamma_{23} & \gamma_{24} & \gamma_{25} & \gamma_{26} \\
\gamma_{32} & \gamma_{33} & \gamma_{34} & \gamma_{35} & \gamma_{36} \\
\gamma_{42} & \gamma_{43} & \gamma_{34} & \gamma_{45} & \gamma_{46} \\
\gamma_{52} & \gamma_{53} & \gamma_{54} & \gamma_{55} & \gamma_{56} \\
\gamma_{62} & \gamma_{63} & \gamma_{64} & \gamma_{65} & \gamma_{66} \\
\end{bmatrix}
\begin{bmatrix}
t_2 \\
t_3 \\
t_4 \\
t_5 \\
t_6 \\
\end{bmatrix}
\]

where
\begin{align*}
\alpha_2 &= -\beta_{12} I_{21} + \beta_{14} I_{23} + \gamma_{24} I_{34} + \gamma_{25} I_{35} + \gamma_{26} I_{36} \\
\alpha_3 &= -\beta_{31} I_{31} - \beta_{33} I_{33} + \gamma_{34} I_{34} + \gamma_{35} I_{35} + \gamma_{36} I_{36} \\
\alpha_4 &= -\beta_{41} I_{41} - \beta_{44} I_{44} - \gamma_{45} I_{45} + \gamma_{46} I_{46} \\
\alpha_5 &= -\beta_{51} I_{51} - \beta_{55} I_{55} - \gamma_{55} I_{55} - \gamma_{56} I_{56} \\
\alpha_6 &= -\beta_{61} I_{61} - \gamma_{64} I_{64} - \gamma_{66} I_{66} - \gamma_{66} I_{66} \\
\end{align*}

and

\begin{align*}
\gamma_{22} &= - (\gamma_{12} + \gamma_{22} + \gamma_{24} + \gamma_{25} + \gamma_{26}) \\
\gamma_{33} &= - (\gamma_{13} + \gamma_{33} + \gamma_{34} + \gamma_{35} + \gamma_{36}) \\
\gamma_{44} &= - (\gamma_{14} + \gamma_{24} + \gamma_{34} + \gamma_{45} + \gamma_{46}) \\
\gamma_{55} &= - (\gamma_{15} + \gamma_{25} + \gamma_{35} + \gamma_{45} + \gamma_{56}) \\
\gamma_{66} &= - (\gamma_{16} + \gamma_{26} + \gamma_{36} + \gamma_{46} + \gamma_{56}) \\
\end{align*}

In the present edition of the program this set of equations was solved by using a canned subroutine. If computer storage becomes a problem the solution vector can be obtained by using a form of the steepest descent algorithm.
GLOSSARY OF PROGRAM VARIABLES

NMIC = Number of Microphones
NL = Number of data points for each microphone
NSW = Number of points in the sliding window
NPFW = Number of points in the Fourier window
SMIC(J,I) = Signal amplitude for MIC J at time I relative to IT(J)
IT(I) = Starting time for microphone I in MSEC relative to blast
LRST(I) = Rough starting point for microphone I relative to IT(I)
NR(I) = Starting time (MSEC) for Fourier window for microphone signal I relative to IT(I)
E(I) = Energy within correlation window for signal I
TAU(J,I) = Raw time difference between windowed signals J and I
RTAU(J,I) = Rough time difference between signal from microphones J and I determined by correlation
CTAU(J,I) = Corrected time difference between microphone J and I by least squared error fit
GAM(J,I) = Normalized correlation coef between signals from microphones J and I
G(J,I) = Reliability weight assigned to RTAU(J,I) for the least square procedure
AT(I) = Time difference shift of signal I relative to MIC 1 signal
TIME(I) = Relative time of the Ith signal for position estimator
A(J,I) = Augmented coefficient matrix for least square fit
JC(I) = Control variable for Subroutine GJR
V(I) = Variables V(1) and V(2) for input to linear equation solution subroutine GJR
CMEAS(I) = Overall measure of correlation for microphone I
X(I) = Ith value of first signal for cross correlation on input
      Ith value of Fourier transfer on output
Y(I) = Ith value of second signal for cross correlation on input
      Ith value of Fourier transform on output
WORK(I) = Work space specified by FOURG subroutine
XX(I) = Ith value of estimate of noise spectrum
YY(I) = Ith value of estimate of signal plus noise spectrum
ZZ(I) = Value at Ith freq for prefilter
IDAY(I) = Day of the start of the Ith microphone signal
IHOURL = Hour of the start of the Ith microphone signal
IMIN(I) = Min of the start of the Ith microphone signal
SEC(I) = Sec of the start of the Ith microphone signal
MIC(I) = PASS microphone number associated with mic I
KMAX = Microphone number selected for reference
TEMP = Effective temperature at time of shot in Deg. C.
MILS = The effective wind direction at time of shot in mils
KNOTS = The effective wind speed at time of shot in knots
KXX = Noise window starting point for SMIC(I,L)
KYY = Noise window starting point for SMIC(J,L)
PREF = Real and imaginary value of prefilter
REFERENCES


