

Measurement of apparent velocity and azimuth of seismic signals recorded at an array

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Abstract. A set of computer programs was written which enables one to determine automatically, the apparent velocity and azimuth of any portion of the seismic wavetrain recorded at various seismic arrays. All that is required to use these programs is that the raw data be available on digital tape and that the user have access to any modern computer. The programs are written in Fortran IV and make use of the adaptive processing method whereby the arrival times of the wavefront at each sensor are accurately determined by cross-correlating the observed wavelet of interest with the corresponding wave on the beam trace. The new arrival times are then used to create a new and improved beam and the whole operation is repeated in an iterative manner until convergence takes place.

Keywords. Apparent velocity; azimuth; seismic signals; array.

1. Introduction

The most significant advantage of a seismic array over a single seismic station is that the slowness (or slope of the travel-time graph), apparent velocity and azimuths can be measured directly from the observations. These measurements are made in addition to the usual measurements of travel-time, amplitude and spectra. The direct measurements of the slope of the travel-time curve as a function of distance can then be used to invert the observations to obtain a velocity-depth curve. Because transition zones, discontinuities, lateral inhomogeneities, etc. may cause multipathing of the seismic energy it is essential that in any detailed study of earth structure, slowness and azimuth measurements must be made over several seconds of the seismic wavetrain after the initial onset. Furthermore because of the great complexities in earth structure and complicated source functions which are usually produced by an earthquake, as many observations as possible should be made in order that statistically significant results can be obtained. The manual method of 'picking' relative arrival times at each sensor from a set of array traces is not only tedious but also does not make full use of the shape of the waveform and hence was not considered by the author. It is therefore necessary that digital methods involving the use of a computer be employed.

In this paper a computer program package is described which enables a user to determine automatically the slowness, apparent velocity and azimuth of any portion of the seismic wavetrain recorded at various seismic arrays. All that is required to use these programs is that the raw data be available on a digital tape which can be

read by any modern computer. The programs are written in Fortran IV and make use of the adaptive processing method whereby the arrival time of the wavefront at each sensor is accurately determined by cross-correlating the observed wavelet of interest with the corresponding wave on the beam trace. The new arrival times are then used to create a new and improved beam and the whole operation is repeated in an iterative manner until convergence takes place. Descriptions and evaluations of the method are given by Gangi and Fairborn (1968), Farrell (1971), Bungum and Husebye (1971), King *et al* (1973), and Mereu and Ram (1975). Apart from the fact that full use is made of the shape of the wavelet to determine accurate values of apparent velocity and azimuth, the method has also an advantage that it can readily be programmed for any moderately sized computer.

2. Program package for seismic data analysis

The computer program package, which was developed, is based on the adaptive processing technique. The method is adaptive in that the delay values resulting from each iteration are used to provide a refined reference signal for the subsequent iteration. The programs were designed primarily for the UKAEA-type medium aperture arrays which have 2 lines called red and blue lines. Should the data come from another type of array, these programs may still be applied without any modification provided the user divides the channels into two groups. This division may be made arbitrarily and should not affect the final answers. The programs were written to handle 36 sec of 20 channel data. If core size is a problem (< 30 K), modifications can easily be made to reduce the amount of data read into the core so that shorter lengths of record (for example 6 sec) are processed at a time. The whole process is then repeated several times to cover the time period of interest. The programs and sub-routines for the adaptive processing techniques were described by Mereu and Ram (1975) and are a rewrite and modifications of the ones written by King *et al* (1973). Those programs were locked into the Australian National University data processing system and were not readily usable outside that system. This package of programs has also attracted the interest of a number of the array seismologists at the Department of Energy, Mines and Resources in Ottawa and at the University of Oxford in England. They have now incorporated these programs into their own research projects.

The computational steps which were taken in the program for this method are given in table 1. The main control parameters and different subroutines required for processing of array data are illustrated in tables 2 and 3 respectively.

Through the use of control cards the user can control the number of measurements (NMEAS) to be made over a coherent wavelet, the size of the windows (WF1, WF2) to be used and the position relative to the centre of the wavelet at which he would like measurements to be made (KBGN). With these options he is able to make measurements over each individual peak and trough separately or if he wishes he may use the whole wavelet at once. He can also make as many measurements as he would like along the coherent event. From a number of preliminary experiments (Ram 1976), it was found that three to five measurements are usually sufficient, the first using the onset of the wavelet, and the last using the tail end of the wavelet with the other measurements overlapping the first and last as shown in Figure 1a.

Table 1. Major computational steps for the measurement of slowness, apparent velocity and azimuth using the adaptive processing programs

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1. Select event, digitise and store on magnetic tape/disk.
 2. Input e.g. SR, expected AZ, slowness, window lengths, filter limits, number of iterations, station co-ordinates, etc.
 3. Data are bandpass filtered.
 4. Calculate initial steering delays.
 5. Form Time Averaged Product (TAP) and initial beam (SRB).
 6. Select all wavelets to be measured automatically from TAP trace.
 7. For each channel: subtract the data of that channel from the beam, evaluate the cross correlation of that channel and the depleted beam, locate the maximum value of the correlation function. The channel is then added back into the beam realigned.
 8. Further refine the revised time delays by using a parabolic interpolation.
 9. Obtain a solution of the normal equations using the refined time delays (Kelly 1964 and Otsuka 1966).
 10. Compare the solution to check for convergence, form new beam, repeat 7-10 until convergence takes place.
 11. Plot and label the records and solutions, print the results together with punched cards and storage on magnetic tape.
- The method is adaptive in that the delay values resulting from each iteration are used to provide a refined reference signal for the subsequent iteration.
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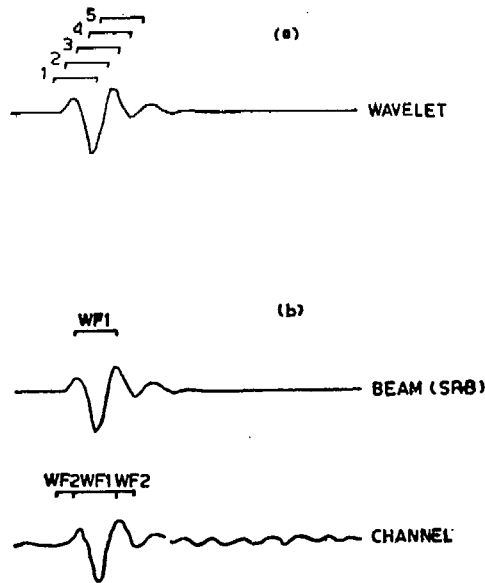


Figure 1 a. Diagram showing how the five measurements are made at different equally spaced locations along a wavelet and **1 b.** Shows the window sizes normally used in the cross-correlation procedure ($WF1=0.75$ sec and $WF2=0.34$ sec.).

The control parameters to set the size of the windows to be used in the cross-correlation procedure are $WF1$ and $WF2$. Their use when applied to a portion of a wavelet is illustrated in figure 1b. The beam signal of width $WF1$ is cross-correlated with the channel trace of width $WF2+WF1+WF2$. The position of the maximum value of this cross-correlation function is used as the relative arrival time position of the wave. Care must be taken not to choose $WF2$ too large as then the correlation functions

may have two maxima and the computer may choose the wrong one for the arrival time position. If by chance the maxima occur at the end points of the correlation function they are rejected as not representing the true arrival time positions. A parabolic fit (subroutine TPARFT) is also made on the three largest values of the correlation function to refine its maximum position.

Aliasing is a problem which can occur when the computer fails to align corresponding peaks on successive traces. Tests with synthetic data showed (Ram 1976) that this tends to occur when the initial trial velocity differs from the true velocity by more than 3 km/sec or the azimuth by more than 8°. The tests also showed that when this occurs convergence usually fails to take place or the standard-errors were

Table 2. Main control parameters

Control parameter	Description	Typical value
SR	Sampling rate per sec.	20
NPT	Number of data points per channel	720
NCH	Number of channels	20
TAPWIND	Window size for time average product (TAP	0.75 sec
WNDEV	Window size for event subroutine	2.0 sec
METHEV	Method of choosing coherent events along trace If METHEV=1, computer finds coherent events for user 1 If METHEV=2, user selects his own coherent events If METHEV=3, computer performs calculations along whole trace	
KBGN	Starting point relative to event of interest	10 units
TLEV	Duration of an event	1 sec
NMEAS	Number of measurements per event	3 to 5
HT	HT=Height of characters to be plotted	
NCHMN	Minimum number of channels to be plotted	1
MCHMX	Maximum number of channels to be plotted (NCHMX=NCH + time channel)	21
GIVSL	Given value to plot slowness axis	11.0 sec/deg
GIVVB	Given value for apparent velocity	10.0 km/sec
GIVAZ	Starting value for azimuth=expected azimuth	
TL	Desired length of band pass filter	3.0 sec
FL	Low pass filter frequency	3.0 Hz
FH	High pass filter frequency	0.4 Hz
WF1	Window size for beam (SRB)	0.75 sec
WF2	Window size for channel traces	0.34 sec
ALEX	Correlation limit value If the average correlation is less than ALEX no answer will be plotted	0.90
JUP1 } JUP2 }	Options to reduce the number of points used to determine the maximum of the correlation function	4 4
KITL	Maximum number of iterations	6
NPUNCH	Gives an option to punch out the results on cards	
NWT	Gives an option to write the results on magnetic tape	

Table 3. List of subroutines required for the adaptive processing package*

Subroutines	Function
BDPSS	Bandpass filter subroutine
CONVL	Filters data using filter weights from BDPSS
DATARAY	Reads array data from magnetic tape
SKIPEOF	Subroutine for DATARAY
ISF	Subroutine for DATARAY
BUFFER	Subroutine for DATARAY
BUFFIO	Subroutine for DATARAY
ARSYNTH	Generates set of synthetic array seismogram
WAVELET	Provides wavelet for synthetic seismogram
ZEROTRC	Zeros the trace of a channel
GVTRC	Subroutine for ARSYNTH
ARRAYA	Calculates polar co-ordinates of each site
DSTANS	Computes angular distance and azimuth
GVTIM	Computes steering delays for each channel
SUMRB	Computes the beam (SRB) and time averaged product traces (TAP)
TSMAX	Finds the maximum value of a given time series and determines its position in time
EVENT	Finds the coherent signals to be processed
WNDF2	Applies a desired window to a time series
ADAPROC	Determines the apparent velocity and azimuth of all coherent signals by adaptive processing
CROSA	Cross-correlates two time series
FASTMX	Fast method of finding the maximum value of the correlation function
TPARFT	Fits a parabola to the peak of the correlation function to refine its maximum position
THREQ	Solves three equations in three unknowns
BEEM19	Calculates a beam minus a channel
BEEMUD	Updates the beam
CROSM	Determines the cross correlation function for two series
BMSHIFT	Shifts the beam by a desired amount
WNDF3	Selects various portions of a time-series to be used
APVEL	Calculates apparent velocities and azimuths using the least squares method
REJKT	Rejects bad channels automatically
TRCPLTA	} Plots the traces of the observed array data
TRCPLTB	
TSYMBAL	
POINT	} Plots an answer point with error bars
EXX	
ANSPLT	Plots the slowness, velocity and azimuth answers
AXPLT	Plots the axes for the final answers

*Subroutines are available from the author on request.

exceedingly large. These solutions were rejected automatically by the computer using present levels of the correlation coefficient.

The following three normal equations as described by Kelly (1964) and Otsuka (1966) are solved using the refined time delays:

$$\sum_{i=1}^N X_i (X_i P + Y_i Q + T_i - T_0) = 0; \tag{1}$$

$$\sum_{i=1}^N Y_i (X_i P + Y_i Q + T_i - T_0) = 0; \tag{2}$$

and $\sum_{i=1}^N (X_i P + Y_i Q + T_i - T_0)^2 = 0; \tag{3}$

where (X_i, Y_i) are array coordinates; T_i is arrival time of wavefront at the i th seismometer as determined by the correlation maximum and T_0 the time at the origin (or cross-over point of the array)

$$P = \sin \phi / V,$$

$$Q = \cos \phi / V.$$

The apparent velocity (V), slowness ($dT/d\Delta$) and apparent azimuth (ϕ) are given by

$$V = (P^2 + Q^2)^{-1/2}. \tag{4}$$

$$\text{Slowness } (dT/d\Delta) = \frac{r_0}{V} = r_0 (P^2 + Q^2)^{1/2}, \tag{5}$$

and $\tan \phi = P/Q; \tag{6}$

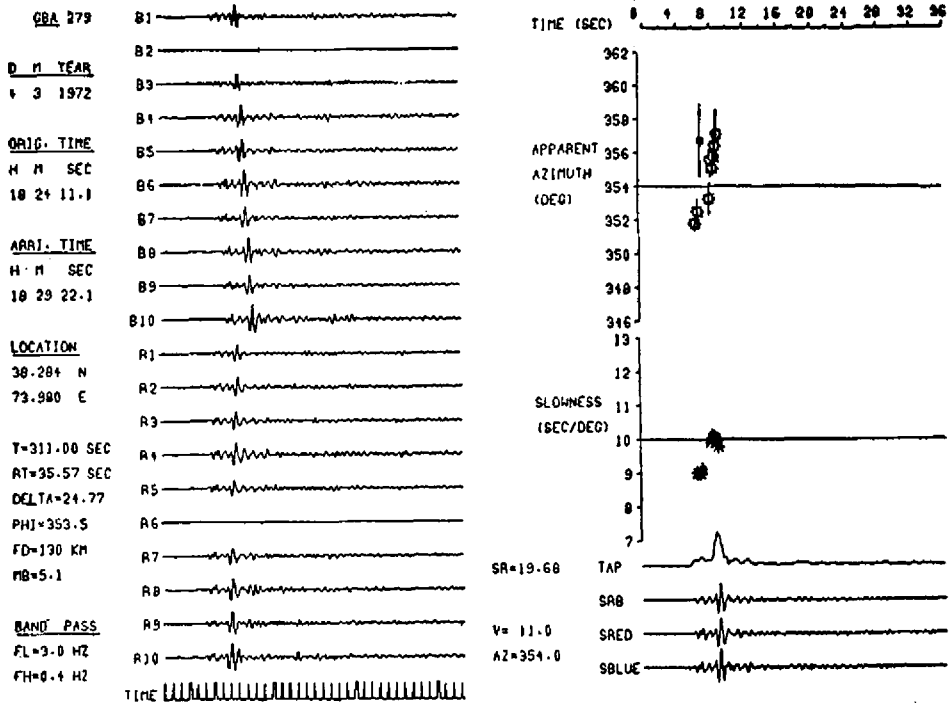


Figure 2. Earthquake recorded at the Gauribidanur Seismic array (GBA), $\Delta_c=25.72^\circ$, Azimuth=353.5° (T=total travel time, RT=reduced travel time, V and AZ are the given apparent velocity and azimuth used to form the initial beam (SRB) and corresponding adaptive processed solution).

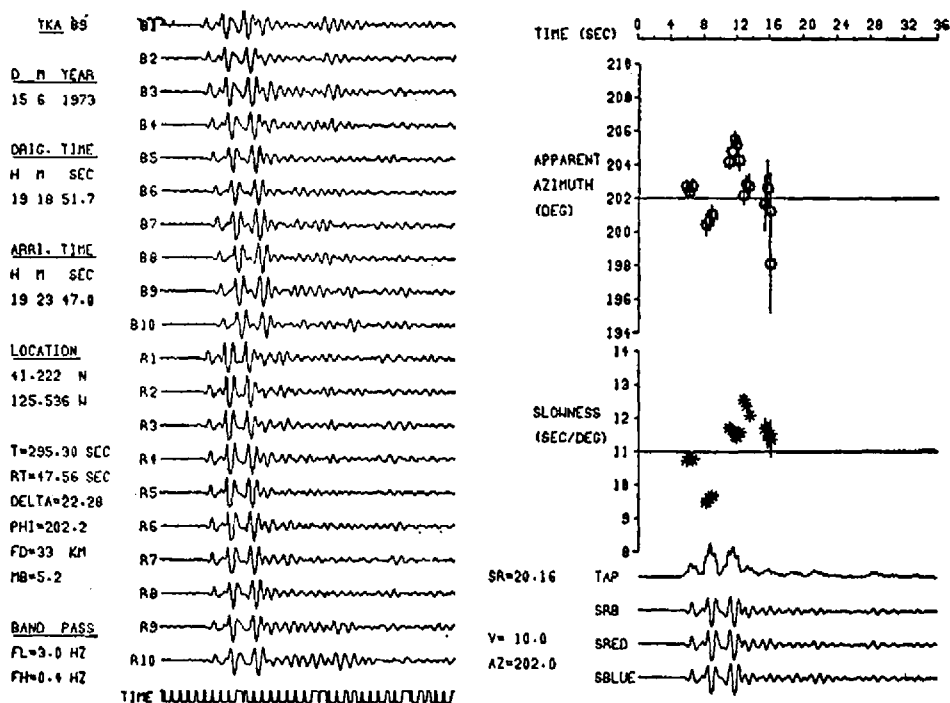


Figure 3. Earthquake recorded at the Yellowknife seismic array (YKA), $\Delta_c=22.52^\circ$, Azimuth = 202.2° (T = total travel time, RT = reduced travel time, V and AZ are the given apparent velocity and azimuth used to form the initial beam (SRB) and corresponding adaptive processed solution).

r_0 is radius of the earth and N represents total number of seismometers in an array. After solving these equations, the solution is checked for convergence. A new and improved beam is formed and the whole operation is repeated (see table 1) until convergence takes place. The results are printed, plotted and written on magnetic tape for further analysis.

3. Examples

The examples shown in figures 2 and 3 are solutions of the events recorded at the Gauribidanur Seismic Array (India) and the Yellowknife Seismic Array (Canada). These events were processed by the CDC CYBER 73 computer at the University of Western Ontario, London, Canada. The total computing time for each earthquake was approximately 90 sec (or about 3 sec for each data point). This includes the time spent in reading the data from the digital tape, filtering, analysing and finally storing the results on a magnetic tape. The total plotting time for the results of each earthquake was approximately 10 min. The error bars are those obtained from the least squares solution. The size of the points used to display the answers is a measure of how well the signals correlated across the array.

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