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Robust Regional Phase Association

by

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Abstract

The need for the rapid association of earthquake phase arrivals arises as one of the major requirements of rapid notification systems. The primary goal of an earthquake early warning system is to warn critical facilities of impending strong ground shaking after rupture in the source region has commenced, but before the arrival of seismic energy (Heaton, 1985; Ellsworth and Heaton, 1994). Recent advances in computer and communications technology make such systems both feasible and practical. Toward this end a phase association algorithm, based on stacking the time-reciprocal regional travel-time function, has been developed; forming the basis of the Auryn phase associator. Earthquake catalogs are adjusted, and locations are recalculated, in real-time as each phase is received. The design is such that hypocenters can be calculated and plotted during vigorous swarms and aftershock sequence.

Future potential applications include shortening of the alarm times prior to large earthquakes, processing amplitude data along with phase arrivals, providing a more robust method of associating phase from sparse regional networks (with possible application to nuclear test ban monitoring, and the association of teleseismic phases from global networks.

Introduction

Association is the process of finding a set of hypocenters that best accounts for a given ensemble of observed arrival times, for various seismic phases, from the stations of a seismic network. Although simple in concept, the algorithms for constructing the hypocenter sequence can be exceedingly complex. Phases from small events and noise sources may not associate. Picks from automated pickers may be mis-identified (e.g. impulsive S arrivals may be represented as P arrivals). Regional phases are even more problematic as regional picks tend to be source magnitude dependent. Distinct events may overlap such that their respective arrivals are intercollated in the pick time sequence; in particular, foreshocks and aftershocks during intense aftershock sequences and swarms often seriously degrade the ability of an association algorithm to distinguish between distinct events. Perhaps the greatest difficulty is that of event "splitting" (Blandford, 1980) wherein the phases for a single event are partitioned between two or more incomplete fragmentary events. This can occur even when all data is correct simply because two events provide more degrees of freedom than one. A bad starting location can cause some correct data to appear to be related to a second earthquake, and any residual data remaining after locating large events will produce a halo of false events surrounding the correct location. This is particularly problematic when there are large numbers of incorrectly identified regional phases (e.g. Pn phases for large events and Pg phases for smaller ones all identified as first P). A robust real-time phase associator must unravel all these complications as they occur, providing an accurate picture while a seismic crisis is unfolding. The general phase association problem is discussed by Allen (1982) and by Lee and Stewart (1979).

Early strategies for earthquake phase association considered all the picks arriving within some time interval and calculated a location assuming all were from a single event. Such systems have been designed and used successfully by Stewart (1977), McEvilly and Majer (1982), and by Johnson (1988). These methods are generally effective during background levels of seismicity, but can fail catastrophically during swarms, aftershock sequences, and occasional coincident events. Secondary events and spatially separated coincident events can easily be missed, and small foreshocks to larger events are particularly difficult to unravel. False picks also pose significant difficulties to time interval association, since they may lead to bad locations, especially if they occur early in the detection interval; an incorrect first pick can completely defeat the starting location strategies of many otherwise well-behaved location programs.

The problem caused by false picks has been circumvented to some extent by more sophisticated methods that calculate modal solutions from an ensemble of possible locations obtained by taking phase arrivals N at a time. Although such approaches have high breakdown thresholds, approaching a tolerance of 50% false picks (Rousseau and Leroy, 1987), the computation time required increases with the factorial of the number of picks tentatively being considered. Allen (1982) used this approach in implementing RTPs (real-time processors) for the USGS Northern California Seismic Network (NCSN), although computational limitations required homogeneous crustal velocity models. Given (1993) describes a similar approach used with the CUSP system at Caltech, wherein combinations of picks are tried until a hypocenter meeting certain acceptability criteria is found. This hypocenter is then used to associate any other picks as they are reported. Phases that are left unassociated, are examined in a similar manner under the assumption that they may belong to a second distinct event more or less coincident in time. Teleseismic and regional variations on this theme have been developed by Engdahl and Gunst (1966) and by Seipp and others (1968). The most important disadvantage of these approaches is that the number of combinations that need to be examined increases with the square of the number of phases being considered, straining computer resources during times of high seismicity such as during aftershock sequences and swarms.

Methods based on expert systems or knowledge based systems should also be mentioned, although they differ markedly from the deterministic method discussed here. One such system, the Intelligent Monitoring System (IMS) as described by Bache and others (1990) is a knowledge based system used to detect possible nuclear detonations. The heart of the IMS associator is an expert system called ESAL (Expert System for Association and Location) developed by Bratt and others (1991). Such systems have great promise for dealing with general detection problems, although they are apparently computationally demanding and may not scale down easily to smaller network applications. A general discussion of the uses of expert systems, with respect to detection and association, is provided by Anderson (1990).

Finally, there is a class of methods based on delay-and-sum beam-forming that may more properly be called detectors than associators. In general such methods apply appropriate delays to seismograms from a small network to increase the signal to noise ratio, for coherent waves with a particular phase velocity, across the array. Mykkeltveit and Bungum (1984) provide a good description of this approach as applied to NORESS small-aperature sub-array of NORSAR. For larger networks, requirements for wave field homogeneity break down, and incoherent methods were introduced. A generalization of these incoherent methods by Ringdal and Kværna (1989) based on stacking seismograms with boxcars at the phase arrival times is remarkably similar to the methodology used in the implementation of the Auryn associator.

Problem

The Auryn associator was designed to provide rapid information concerning the location and size of an earthquake within seconds of its occurrence. Arrival times from earthquake phase pickers, running in real-time, are analyzed as they become available in order to calculate the location and size of an earthquake as quickly as possible. Typically, with a station spacing of 15 km and a picker latency of 3 seconds, appropriate for pickers based on the algorithm described by Allen (1978), preliminary locations can be available in about 10 seconds or less. The primary limitation here is just the time it takes energy to reach a sufficient number of sensors so as to make a reliable event identification and hypocentral calculation possible.

Formulation

Mathematically, the association process can be understood by considering two evolving time sequences, each of whose members are points in a four dimensional space comprising three spatial coordinates and time. The first sequence comprises phase arrivals from a seismic network, with elements of arrival time and the spatial coordinates of the seismic station. Without significant loss of generality we can assume that the members of this sequence arrive in time order so that the sequence Phs_i, after the arrival of the i^{th} phase, can be taken as

$$Phs_i := \{\ldots, phs_{i-2}, phs_{i-1}, phs_i\}. \tag{1}$$

In addition to the four principal parameters, each phase may have related parameters such as suggested phase identification, impulsivity, temporal resolution, wave amplitudes and direction of first motion.

Within this context, the association process becomes that of finding a related sequence of earthquakes

$$Hyp_i := \{\ldots, hyp_{i,j-2}, hyp_{i,j-1}, hyp_{i,j}\}, \tag{2}$$

which represents in some manner the "optimal" sequence associated with Phs_i after the addition of the i^{th} phase. (This notation is chosen to emphasize the fact that the time ordered sequence of hypocenters may change with the arrival of each reported phase.) For the standard earthquake location problem, where phases are winnowed by hand and incorrect phases are deleted, Phs_N is just the total database of N earthquake phases, and Hyp_N is the resulting catalog of hypocenters.

Identifying an optimal sequence of hypocenters requires defining a norm or metric, on the space of all possible such sequences, that can be minimized to identify the "best" sequence. For this purpose we define an association matrix, as shown in Fig. 1. The elements of the association matrix, $\mathbf{A_{i,j}}$, are:

$$A_{i,j} = \begin{cases} \frac{W}{(W+N_j)} \left| \frac{Tobs_i - Tcal_{i,j}}{\Delta(r_{ij})} \right| & \text{If } phs_i \text{ is associated with } hyp_j \\ 0 & \text{Otherwise} \end{cases} \tag{3}$$

where $\mathbf{Tobs_i}$ is the arrival time of phase $\mathbf{phs_i}$, $\mathbf{Tcal_{i,j}}$ is the calculated arrival time for the i^{th} phase from the j^{th} hypocenter, and $\mathbf{N_j}$ is the number of phases associated with the j^{th} event. A tolerance function, $\mathbf{\Delta(r_{ij})}$, defines the maximum acceptable residual for association, given the epicentral distance, and also normalizes the travel-time residual to the unit interval. The parameter, $\mathbf{W}$, is a weighting parameter that substantially reduces event "splitting" by permitting larger events (e.g. those with more associated picks) to associate phases with larger residuals. It is analogous to the F-test in least squares inversions, in that it suppresses the tendency to increase the model's degrees of freedom, when it is not warranted by the data.

A simple example of the association matrix is shown in Fig. 1. Columns of the association matrix represent hypocenters and each row represents a discrete phase arrival. Non-zero elements of the association matrix are travel-time residuals normalized according to Eq. 3 and are located in the column for the hypocenter with which they are currently associated. No phase is permitted to be associated with more than one earthquake so that no row contains more than one entry. Arrivals for which the normalized residual exceeds 1.0 are plotted as a '*' in the left most column and are considered unassociated.

Within this framework, the association process involves moving residuals between columns so as to minimize the value of the association norm

$$Norm = \Sigma_{i,j} A_{i,j}. \tag{4}$$

The first picks to arrive for a new event will be unassociated until a sufficient number have accumulated to constrain a new trial event, at which time a new column in the association matrix is created. At other times, the movement of arrivals between columns may result in one with insufficient arrivals to constrain a location; such columns are deleted and all picks are marked as unassociated. This occurs, for instance, when a large event is initially "split" and subsequently one sub-event gains a sufficient number of arrivals to "crowd out" the smaller sub-events, and acquire the phases assigned to the others.

Method

The implementation of the Auryn associator comprises two discrete operations. As new phases arrive, each is compared for consistency with all possible branches of the travel-time curves from known events. In terms of the association matrix, a new row is created, and an entry is made in the column which provides a minimum $\mathbf{A_{i,j}}$ calculated from Eq. 3. A necessary condition for association is that the travel-time residual normalized by $\Delta(\mathbf{r_{ij}})$ not exceed 1.0. Modified hypocenters, columns in the association matrix, are relocated and the resulting residuals are examined to ensure that all continue to meet the $\Delta(\mathbf{r_{ij}})$ association condition. Those failing this test are marked as unassociated, a process referred to as culling, and may when combined with other unassociated arrivals lead to the creation of an additional column in the association matrix. Subsequently, during a scavenging process, residuals for phases associated with other events are examined to determine whether the overall association norm specified in Eq. 4 would be minimized if they were reassigned to a newly modified event. It should be noted that this procedure is exceedingly nonlinear and combinatorial in nature. As a result of reassociating a phase, both the receiving and losing events must be relocated. All residuals for both events will in general be changed, and this in turn might result in additional scavenging and culling. As a result of scavenging, multiple columns containing phases from a single event are merged, thus dealing with the notorious "splitting" problem. Phase arrivals that fail to be associated with known hypocenters enter a spatio-temporal stacking process. Phase stacking results in the generation of new columns of the association matrix and is the principle way by which the Auryn phase associator differs from previous approaches.

The stacking algorithm was motivated by the "string" method (Richter, 1958) of locating earthquakes from measurements of P and S arrival times. A length of string cut to the appropriate distance was used to draw a circle on a map representing the locus of possible locations compatible with the observed S-P duration (distance in km is about 8.0 times the duration in seconds) at several stations. The earthquake was then assigned a location near the intersections of the circles from at least three stations. Fig. 2b shows how these circles would be drawn for three stations (triangles) based on a hypothetical shallow quake marked with a circled asterisk. Each circle represents the locus of possible epicenters from independent P and S measurements at a single station, and as expected they intersect at the known location. To illustrate how this might be thought of as a stacking approach, the plot has been divided into 10 km cells, and each cell contains the count of the number of loci that fall within 10 km of its center. The known location falls within the cell with the highest "hit" count.

Shallow earthquakes and phase arrivals can both be represented as points in a space-time volume with two spatial axes and one time axis. P-wave arrivals for a given earthquake will be found on a funnel shaped surface of revolution about the positive time axis through the space-time point representing the earthquake. The equation governing the locus of phase arrivals for a given earthquake can be expressed as

$$T_{quake} + T_p(r_{quake}, z) = 0.0 \qquad (5)$$

where $\mathbf{T_{quake}}$ is the event origin time, and $\mathbf{T_p}$ is the P-wave travel-time calculated as a function of epicentral distance, $\mathbf{r_{quake}}$, and source depth **z**. For the simple example, **z** is taken to be 0.0. The cross-section of this surface of revolution is the P-wave travel-time curve. The arrival times of other phases are found on similar surfaces of rotation reflecting the appropriate branches of the regional travel-time curve. By reciprocity, the quake will be found near the intersection of the same surfaces of rotation plotted negatively in time with apices at the associated phases. For a particular phase, the equation for the locus of possible hypocenters is simply

$$T_{phase} - T_p(r_{sta}, z) = 0.0 \qquad (6)$$

where $\mathbf{T}_{phase}$ is the arrival observed time and $\mathbf{r}_{sta}$ is the distance measured from the recording seismometer. To illustrate this, consider P arrivals recorded at three stations, CEJ, BMB, and ANB, from an event at the surface of a homogenous half-space with a velocity of 5 km/s as shown in Fig 2. Fig 2b, which corresponds to the "string" location discussed above, is also just the temporal cross-section through all such surfaces given by Eq. 6 at the event origin time. The cross-section 2 seconds after, and 2 seconds before, the origin time are shown in Fig. 2a and 2c respectively. In these three figures, dashed lines indicate where two space-time cross-sections are drawn in Fig. 2d and 2e, which reveal more clearly the shape of the travel-time branches plotted with respect to negative time. The counts correspond to the number of hypocentral loci that fall within 1.8 seconds of the center of each space-time cell. As before, the actual hypocenter falls near the modal location of all cells with a count of 3.

With each new phase, the association stack is constructed and examined to determine whether the count for any cell exceeds some threshold; at least 4 if depth is included. If so, a new earthquake is created, a column is added to association matrix, and the hypocenter is calculated using the centroid of all cells meeting the threshold condition as a starting location. In current implementations of the Auryn associator, a least absolute residual approach, (L1), is used to locate the trial hypocenter, for consistency with the association norm described in Eq. 4. In a very real sense, the stacking process is actually a form of very robust, nonparametric location methodology, as was its predecessor, the "string" method.

One difficulty with the approach outlined above is that there is always a trivial solution to the problem of minimizing the norm defined in Eq. 4, and that is to assign a hypocenter to each subset of four arrivals, resulting in residuals of 0.0s for those stations, and a norm of 0.0. (This is another way of illustrating the inherent difficulty of avoiding "split events.") One rough-and-ready approach to this difficulty is to apply Occam's razor with a vengeance.

One could take the hypocenter list, and scan it for events which are close enough in space-time, that they might be split fragments of the same event. (This will basically involve checking to see if the difference in their epicenters is less than the difference in their origin times, multiplied by 6 km/s.) If two events qualify as a potential split, combine their phases, and see if they will locate. If they will locate without blowing up, and if the RMS does not increase by more than would be expected for the decrease in free parameters (two earthquakes have 8 degrees of freedom, combined they only have four), then they are one event, and the hypocenter list is shorter by one. This process can be continued until there are no more candidates to try.

In terms of the norm for the association matrix defined by Eq. 4, this could be thought of as defining a modified **Norm,** which is to be minimized by combining sub-events, and including more arrivals, until no further simplification of the association matrix is possible:

$$Norm_n^r = \sqrt{\frac{n}{(n-r)}} \sum_{ij} A_{ij} \qquad (7)$$

where **n** is the number of phase arrivals, and **r** is the degrees of freedom used in the "solution". Since each hypocentral estimate has four degrees of freedom associated with it, and in some sense each unassociated arrival adds a single degree of freedom, **r** will equal four times the number of events, plus the number of unassociated arrivals.

This is not correct, strictly speaking, of course, since it applies to an L2 norm in the limit of large n, and Auryn uses an L1 norm. However, it does have the desirable properties of favoring a norm that minimizes the number of events, and the number of unassociated arrivals. In practice, it will be the success of this approach that will determine its usefulness, rather than its theoretical justification. The important point is that this approach directly addresses the splitting problem in a manner that can be efficiently implemented.

Applications

The Auryn associator was designed to provide rapid earthquake locations for a local seismic network with a disorderly station distribution and non-uniform station density. For parts of the network with station spacing of about 15 km and a picker latency of 3 seconds preliminary locations are available in principle in about 10 seconds after the origin time. The associator was designed to provide reliable locations soon enough after the occurrence of a large event in California to be of practical benefit, and to this end the developments based on the Auryn algorithm have are proceeding satisfactorily. Running on a Sparc10, the time to process a single phase is less than 0.1s (about 1s on a Sparc 1). Implementations of the Auryn associator run on UNIX, Solaris, and MS Windows 3.1 operating systems.

During 1993-4 the Auryn associator has been in use integrating phase picks from 400 stations of the USGS Northern California Seismic Network in Menlo Park, California. Prior to its use, existing systems had been providing multiple alarms for large earthquakes as independent systems individually reported occurrence. Quakes falling between subnets were often mislocated by one or more processors. The ability of the Auryn associator to avoid splitting events is one of its most important characteristics, and while this is a very difficult problem (see Discussion below), progress is continuing in tuning the program to minimize the number of splits. Our experience at this point suggests that it will be possible to reduce the number of splits to an acceptable level.

Presently the Auryn associator is being run on UNIX machines at Caltech, USGS Menlo Park, University of California at Berkeley and the University of Hawaii at Hilo. The current version is capable of exchanging phase data over the INTERNET. The associator running in Hilo has, from time to time, processed phase data from the combined Southern California Seismic Network, and the Northern Seismic Networks - a combined instrument total exceeding 800 sensors over an area more than 1000 km along the entire length of the San Andreas fault with a average width of 450 km. This arrangement is particularly exciting for quakes occurring between the networks, where individually neither network can provide nearly the constraint available in the combined data set. Sources of data in the configuration included three RTPs, a prototype 256 channel independent real-time picker (Dietz and others, 1993), and phase arrivals from the CUSP system in Southern California as described by Given (1993).

The system running at the University of California at Berkeley (UCB) provides the basis for rapid notification in Central California; combining data from the NCSN (via INTERNET) with a sparse network of high performance seismometers telemetered directly to UCB. This illustrates the strengths of the current implementations of the Auryn associator, in its ability to run on, and integrate, phase data from diverse platforms; the capability to exchange data over wide-area networks; and the ease with which multiple branches of the regional travel-time curves can be resolved in real-time as phase data is being received.

Discussion

The association problem divides into three interconnected subsets of problems. They are:

1. Identification
2. Location, and

3. Selection, or association,

Steps 2 and 3 will be looped through many times, as more arrivals come in, are associated with an event, the event relocated, etc..

A fourth step should probably be included, which can be roughly characterized as:

4. Clean-up.

Identification is simply the identification of some subset of the phase list as (potentially) corresponding to a single earthquake. This is usually an extremely non-unique identification, and the events initially selected are in reality only trial events, to be evaluated in the following steps. The Auryn stacker described above performs this task in a very general, and very efficient manner, and is in essence a generalization to all possible combinations of the "four-at-a-time" algorithm referred to above (Allen, 1982).

Location is assigning of a trial hypocenter and origin time (and sometimes magnitude) to the trial phase list. Given the non-linear character of the earthquake location problem, this also is often an ill-determined, and often unstable process. In particular, the identification of a initial guess hypocenter from which to begin the iterative location procedure is extremely critical, given the possibility of multiple local minima, only one of which corresponds to the "true" earthquake location. In a real-time "look-ahead" associator such as Auryn, where an updated estimate of the earthquake location is attempted each time a new piece of information is obtained, this is an extremely difficult step, because of the potential instability of the location procedure when using a small number of phase arrivals, particularly in the presence of noise. The Auryn associator is very helpful at this stage, because in addition to identifying that a set of arrivals potentially correspond to an earthquake, Auryn provides an extremely robust trial hypocenter, and it is bad initial guesses that plague interactive location procedures.

Selection involves the identification of additional phase arrivals because they fit within a phase velocity window projected out from the trial hypocenter. As additional arrivals are added to a trial hypocenter, the location step can be repeated, followed by additional selection, location etc.

It is very important at this point to properly assess the uncertainty in the arrival time estimates used to select phases, if one is to avoid split events that result from leaving too many orphan arrivals unassociated. It must be remembered that this uncertainty includes contributions from the origin time and location uncertainty for the earthquake hypocenter. These contributions are often very large for earthquakes located with only a few arrivals, or those located outside the seismic network.

Clean-up includes the rejection of trial events on the basis of supplementary criteria such as the dispersion of the travel time or magnitude residuals, the shape of the coda decay, the frequency content of the associated phases etc. In addition, the hypocenter list can be examined at this point to see if there are multiple locations for the same event; if multiple locations are found for a single event, the process may have to return to the location step. A straight-forward application of Occam's razor at this stage is to simply combine two trial events that might belong together, and relocate them. If they do not belong together, the location procedure will blow up.

Trade-offs

Taken in a broad context, the real time earthquake association and location problem can be characterized in terms of a number of trade-offs; how a system performs under various circumstances will be determined largely by how these trade-offs are resolved.

The problem begins with the processing of the digital seismic traces to produce "picks"; (potential) phase arrivals that consist of an arrival time, a first motion, an amplitude, and one or more measures of uncertainty. In some cases there may also be a phase velocity from a small array, particle motion directions, or some measure of the frequency content. The essential trade off in designing pickers is how discriminating they are in producing picks for only the desired class of seismic events. Tight pickers produce relatively few picks, with high signal-to-noise ratios, for only those arrivals that correspond precisely to those produced by the target events; loose pickers produce picks, some with low signal-to-noise ratios, for a wide variety of events. Since there are "costs" associated with both strategies, trade-offs are required. In the case of a general purpose seismic network (like the NCSN), a wide range of event types must be identified, ranging from small high frequency events at short distances, to deep low frequency volcanic events, to distant regionals, to teleseisms. Thus Pickers for such a net must be "loose" or "promiscuous", which results in a relatively high "noise level" of unwanted picks, and results in a more difficult association problem.

Associators are also characterized by a trade-off in how discriminating they are. A "loose" associator sweeps up everything in sight, and lets the locator try to resolve the large residuals; this will result in many events associated, few split events, some instabilities in location, and a high level of "noise events." A tight associator will associate fewer events, will split more events, will produce very stable locations (which for split fragments will sometimes be incorrect), and will have a low level of noise events (except those generated by splitting.)

For a general purpose network compromises will have to be made, but in general they will have to err on the side of loose pickers, coupled to loose associators; the "costs" associated with missed events are too high, particularly in volcanic regions. This will result in a high level of noise events which will have to be weeded out downstream.

A better alternative is to move beyond associating simply on the basis of arrival times, and begin to use additional criterion. The obvious first step is to include the amplitude of the arrivals in the association process itself. An earthquake is not an abstract entity characterized by a propagating envelope in space-time, but consists of an envelope of elastic energy, spreading and being absorbed in a real earth. Thus a real earthquake is characterized by pick amplitudes which in general decay with distance, usually in a reasonably well-defined way. This is in principle a very powerful discriminant against noise events, since very few of those events which mimic an earthquake in phase space, will have a physically plausible pattern of amplitude decay in energy space.

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Figure Captions

Fig. 1. The relationship between a sequence of phases and related hypocenters can be expressed in the form of a matrix, where hypocenters are represented as columns and phase picks as rows. Matrix entries correspond to values of the normalized residual expressed as Eq. 3. Each phase can be associated with at most one hypocenter, so each row has only a single entry. The left-most columns shows phases that have not been associated with any event.

Fig. 2. Each phase and each earthquake can be represented as discrete points in a four dimensional space comprising three spatial dimensions and 1 time dimension. For illustration purpose this has been reduced to two spatial dimension by considering only surface focus events. For each phase, there exists a two-dimensional surface which is the locus of possible hypocenters consistent with the arrival time and the location of the recording sensor

(plotted as inverted triangles). In 1a through 1e three sections of this space are provided, with curves showing the intersection of each of these surfaces. Counts within each cell denote the number of such surfaces near the center of each. Since an associated event must lie near the intersection of all such surface, it should be found in or near the cells with the highest counts, thus defining both the associated phases and the starting location. The first three plots, 1a - 1c show spatial plots plan views at two second intervals, with the actual point representing the hypocenter plotted in 1b. Dashed lines on these sections show the position of two time-space plots paralleling the time axis and plotted in 1d and 1e.

References

Anderson, K. R. (1978). Automatic processing of local earthquake data. M.S. Thesis, Massachusetts Institute of Technology, 173p.

Anderson, K. R. (1990). Programming as a geophysical inverse problem. *Bull Seism. Soc. Am.* **80**, 1893-1909.

Allen, R. V. (1978). Automatic earthquake recognition and timing from single traces. *Bull. Seism. Soc. Am.* 68, 1521-1532.

Anderson, R. V. (1982). Automatic phase pickers: their present use and future prospects. Bull. Seism. Soc. Am. 72, S225-S242.

Bache, T. C., S. R. Bratt, J. Wang, R. M. Fung, C. Kobryn, and J. W. Given (1990). The intelligent monitoring system. *Bull. Seism. Soc. Am.* **80**, 1833-1851.

Blandford, R. R. (1982). Seismic event discrimination. *Bull Seism. Soc. Am.* 72, S69-S87.

Bratt, S. R., G. W. Beall, H. J. Swanger, F. K. Dashiell, and T. C. Bache (1991). A knowledge-based system for automatic interpretation of seismic data to associate signals and locate events. NMRD Quarterly Technical Report #8, DARPA Contract Number MDA972-88-C-0024.

Dietz, L. D., W. Koehler, and W. L. Ellsworth (1993). A real-time p-wave picker (RTP) for a fast earthquake response system (Earthworm). *Eos, Am. Geophys. Union Trans.*, **74**, p. 429.

Ellsworth, W.L. and T.H. Heaton (1994). Real-Time Analysis of Earthquakes: Early-Warning Systems and Rapid Damage Assessment, *Sensors, 11*, 27-33.

Given, D. D. (1993). Operators guide to ISAIAH: Information on seismic activity in a hurry. (Preliminary draft)

Heaton, T.H. (1985). A Model for a Seismic Computerized Alert Network, *Science*, __, 987-990.

Johnson, C. E., English, T. T., and Koyanagi, R. Y., 1988, A data processing system for the effective management of a volcanic crisis. *Eos, Am. Geophys. Union Trans.*, **69**, p. 1049.

Lee, W. H. K. and S. W. Stewart (1979). Principles and applications of microearthquake networks. USGS Open-file report 79-xxx.

McEvilly, T. V. and E. L. Majer (1982). An automated seismic processor for microearthquake networks. *Bull. Seism. Soc. Am.* **72**, 303-325.

Mykkeltveit, S., and H. Bungum (1984). Processing of seismic events using data from small-aperture arrays. *Bull. Seism. Soc. Am.* **74**, 2313-2333.

Ringdal, F. and T. Kværna (1989). A multi-channel processing approach to real time network detection, phase association, and threshold monitoring, *Bull. Seism. Soc. Am.* **79**, 1927-1940.

Rousseeuw, P. J. and A. M. Leroy (1987). Robust regression and outlier detection. John Wiley and Sons, New York, 329p.

Seipp, L. J. Johnson, G. Clawson, and D. Peck (1968). ADAPS-An automatic data association and processing system for seismological data. *TR*-68-28, Teledyne Geotech, Garland, Texas.

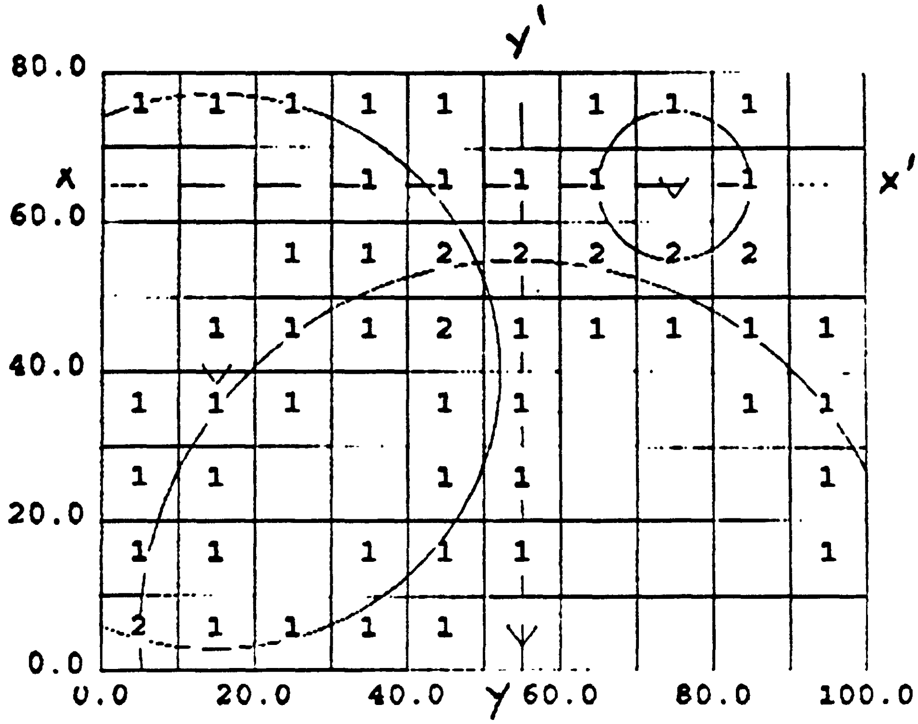
Stewart, S. W. (1977). Real-time detection and location of local seismic events in central California. *Bull Seism. Soc. Am.* **67**, 433-452.

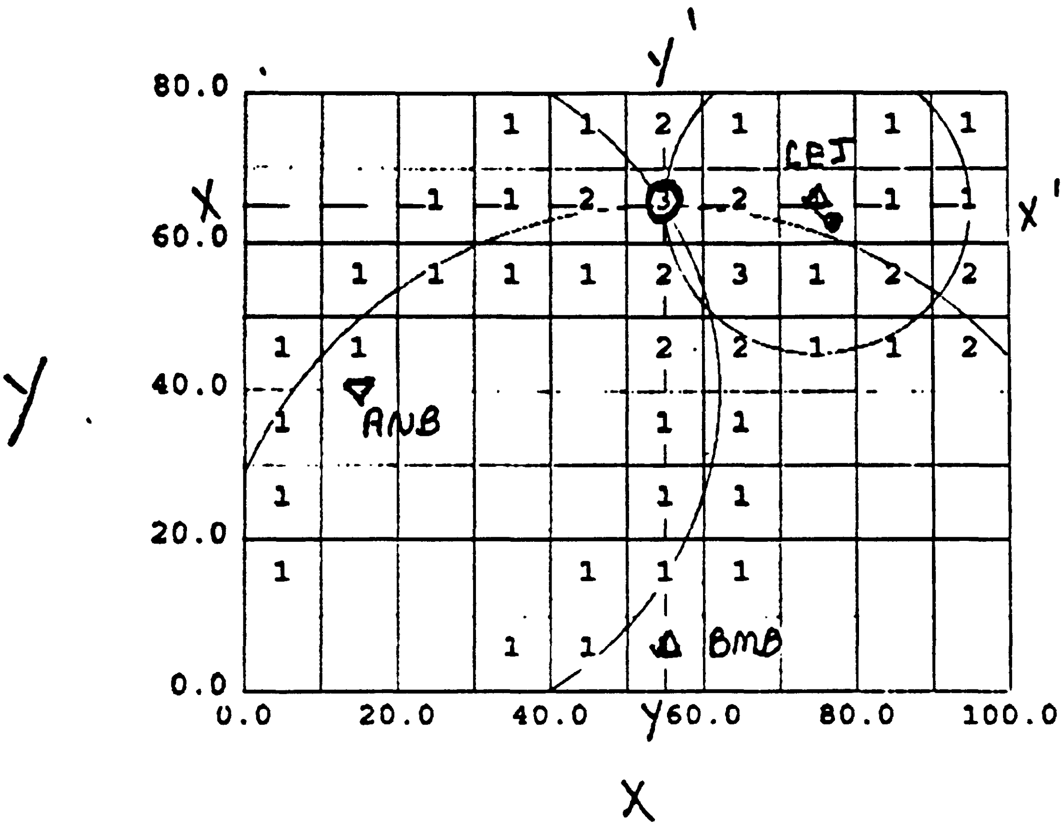
Wirth, M. H. and R. B. Blandford and R. H. Shumway (1976). Automatic seismic array and network detection. *Bull. Seism. Soc. Am.* **66**, 1375-1380.

Fig. 1

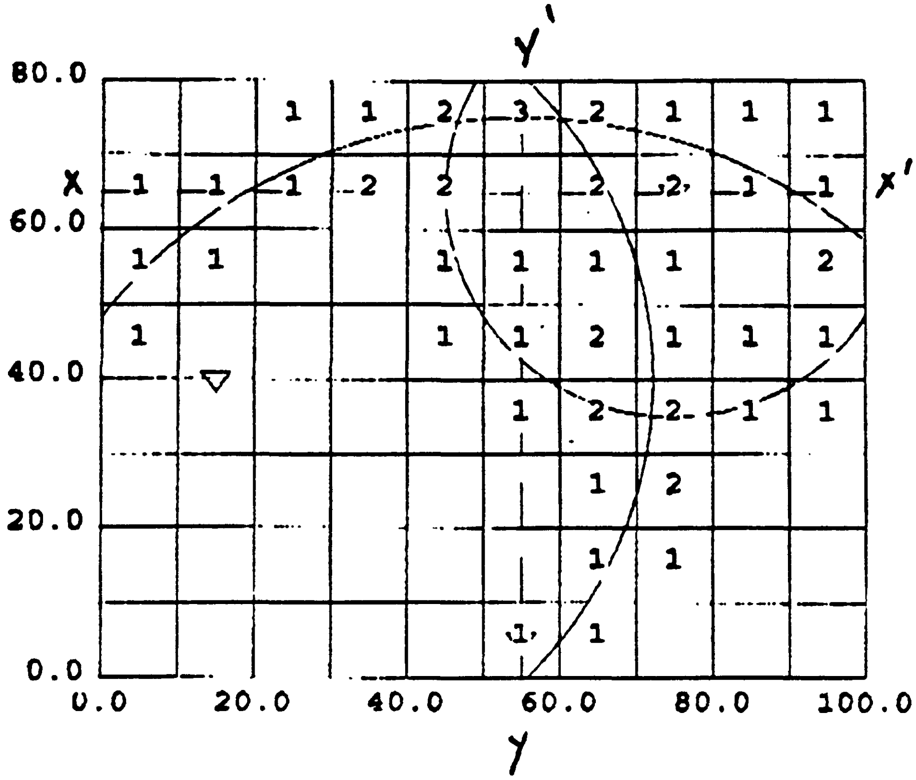
	Null	hyp_j	hyp_{j-1}	hyp_{j-2}
phs_i	*			
phs_{i-1}	*			
phs_{i-2}	*			
phs_{i-3}		0.13		
phs_{i-4}		0.08		
phs_{i-5}		0.06		
phs_{i-6}		0.01		
phs_{i-7}		0.05		
phs_{i-8}		0.02		
phs_{i-9}		0.02		
phs_{i-10}		0.01		
phs_{i-11}	*			
phs_{i-12}			0.01	
phs_{i-13}			0.02	
phs_{i-14}			0.05	
phs_{i-15}			0.08	
phs_{i-16}			0.04	
phs_{i-17}				0.04
phs_{i-18}				0.03
phs_{i-19}				0.02
phs_{i-20}				0.01

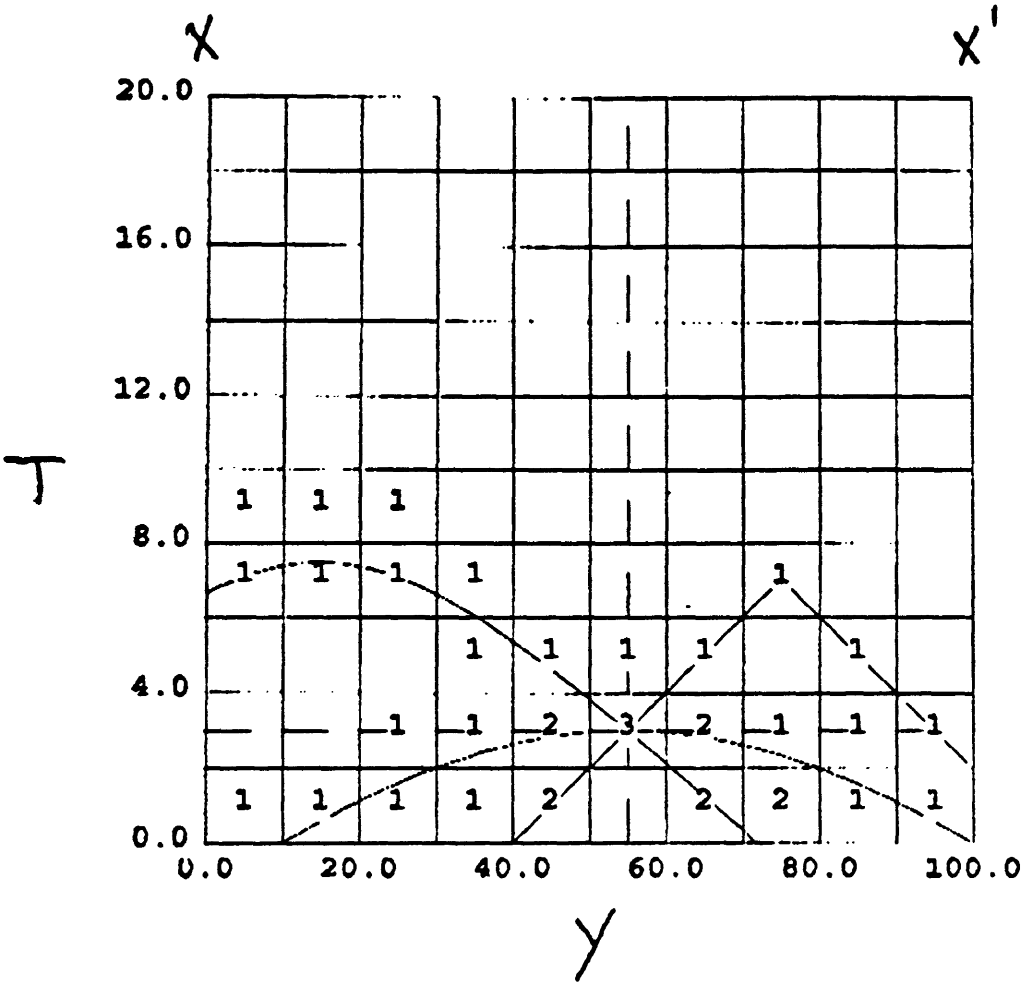
2a

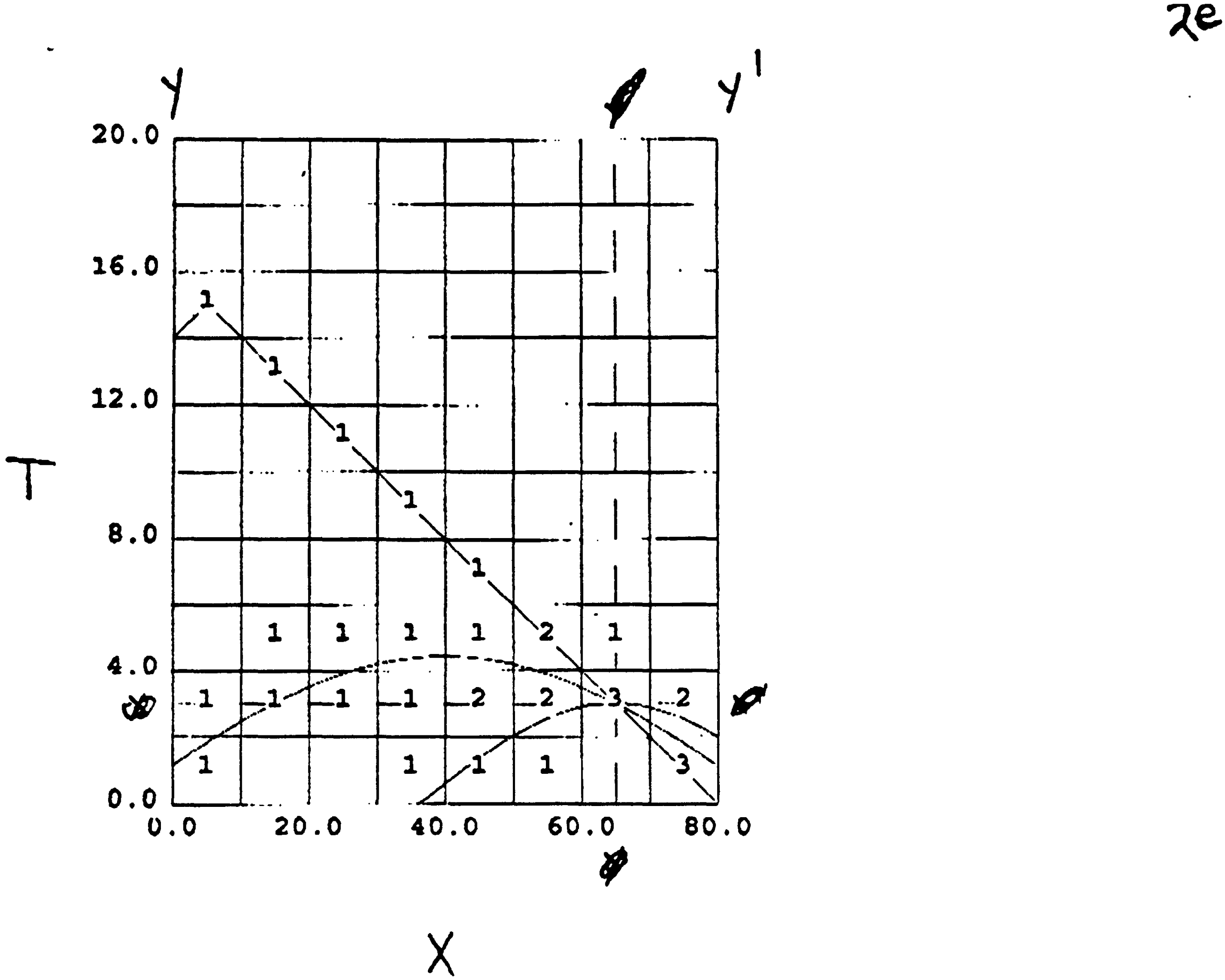



Y'
X
X'
Y
CPJ
ANB
BMB
80.0
60.0
40.0
20.0
0.0
0.0
20.0
40.0
60.0
80.0
100.0
X

2c




X
X'
T
20.0
16.0
12.0
8.0
4.0
0.0
0.0
20.0
40.0
60.0
80.0
100.0
Y


2e
Y
Y'
T
X
20.0
16.0
12.0
8.0
4.0
0.0
0.0
20.0
40.0
60.0
80.0