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AUTOMATIC PHASE PICKERS: THEIR PRESENT USE AND FUTURE PROSPECTS

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ABSTRACT

Automatic phase-picking algorithms are designed to detect a seismic signal on a single trace and to time the arrival of the signal precisely. Because of the requirement for precise timing, a phase-picking algorithm is inherently less sensitive than one designed only to detect the presence of a signal, but still can approach the performance of a skilled analyst. A typical algorithm filters the input data and then generates a function characterizing the seismic time series. This function may be as simple as the absolute value of the series, or it may be quite complex. Event detection is accomplished by comparing the function or its short-term average (STA) with a threshold value (THR), which is commonly some multiple of a long-term average (LTA) of a characteristic function. If the STA exceeds THR, a trigger is declared. If the event passes simple criteria, it is reported. Sensitivity, expected timing error, false-trigger rate, and false-report rate are interrelated measures of performance controlled by choice of the characteristic function and several operating parameters. At present, computational power limits most systems to one-pass, time-domain algorithms. Rapidly advancing semi-conductor technology, however, will make possible much more powerful multi-pass approaches incorporating frequency-domain detection and pseudo-offline timing.

INTRODUCTION

Automatic phase pickers are devices used to scan seismic traces in search of phase arrivals, and when an arrival is detected to measure the relevant parameters required by a seismologist studying the earthquake. A "picker" thus incorporates the function of a "detector"—recognition of a seismic phase arrival in the presence of background noise but the picker must also perform the more precise measurements required for location and further study of the earthquake. The parameters measured will include, at a least minimum, the arrival time and some measure of the size of the event, and should include direction of first motion and a number expressing the "weight" or confidence to be accorded this pick in further processing. In some cases these parameters may include spectral distribution plots, and in principle they can include the complete digital record or "squiggly line." The completeness of the report list actually prepared by the picker will be governed by such constraints as computational power available per seismic channel and recording space available for the results as well as by the desires of the seismologist using the data.

The most important difference between a phase picker and a phase detector is the required precision of timing of the moment of first arrival. A picker must time a good phase arrival with a precision of no worse than a few hundredths of a second, whereas a detector usually is allowed at least a second of leeway; commonly more. This difference dictates that the very powerful frequency-domain methods available to detectors are not immediately applicable to pickers. In frequency domain analysis, a section of record is examined for the presence of a specified spectral distribution which indicates seismic energy in that section of record. The power of the method to detect and resolve the specified spectral distribution in the presence of masking noise is dependent on the length of the window, but the timing precision, the ability to specify at exactly which sample the seismic energy first appears, is inversely proportional to this window length. For precise timing, the picker must search for a rapid change of amplitude or dominant frequency as apparent in the time sequence of digital samples.

Berger and Sax (1981) presented a survey of phase detectors and pickers including a comprehensive bibliography and historical survey. In this report I discuss pickers that have been implemented and are or have been used in practical applications of seismic studies with microearthquake nets. These pickers are designed for use with phase arrivals from earthquakes generally less than 150 km away; local to near-regional events of the kind that networks commonly are set up to observe. Unless stated otherwise, the term "phase" or "phase arrival" refers to P, not S waves.

The operational pickers which best represent current practice in automatic processing are those described by Matsumura and Hamada (1976), Stewart (1977), Matsumura *et al.* (1981), and the U.S. Geological Survey (USGS) Calnet system using Allen's (1978) algorithm as implemented on multi-processor hardware designed

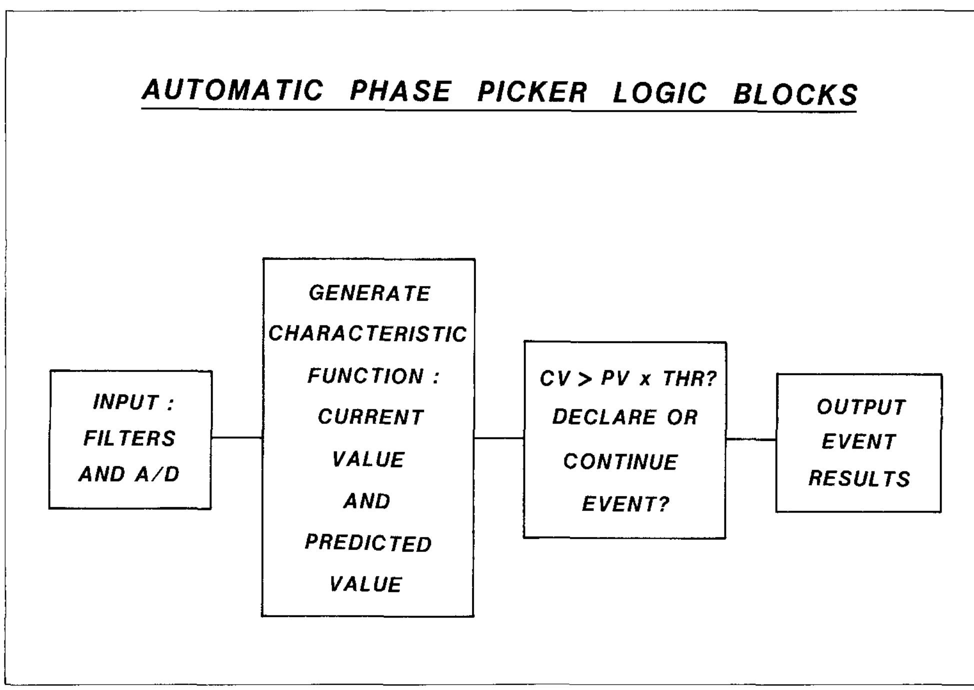

FIG. 1. Block diagram illustrating generalized picker logical structure.

by Ellis and Rodriguez (unpublished data), and the automatic seismic processor (ASP) system of McEvilly and Majer (1982).

Large parts of a picker could, in principle, be accomplished by analog techniques, such as those used in the detector developed by Ambuter and Solomon (1974). The advantages of digital processing, however, such as improved signal-to-noise ratio during processing and much wider range of available processing algorithms, make unlikely any future effort to use the analog approach except for antialiasing input-data filters. In this discussion I assume that all pickers are based on algorithms implemented in digital techniques.

Logical Structure

The logical structure of all pickers is strikingly similar and may be described by the logic block diagram of Figure 1. The first block is the input section including the input filter and analog-to-digital converter. Part of this block is the antialiasing filter, and part may well be an implicit filter resulting from overall system response. In most applications this filter is a band-pass, and in some rather special applications it may include two or more separate pass bands. Evans and Allen (1982) reported a teleseism detector whose operation depends critically on energy in two separate pass bands, and whose input stage incorporates appropriate filters. Most systems now in use digitize at a resolution of 12 bits (1 part in 4096) at a sample rate of 50 to 200 samples/sec. A few systems operate with a resolution of up to 16 bits and sample rates of 1000 or more per second. The choice of these parameters depends on the use to be made of the output data.

After digitizing a sample, some algorithms skip ahead to the "declare or continue?" choice if an event has been declared and is in progress; otherwise, the picker proceeds to the second block which represents a process that generates the characteristic function (CF), a new time series characteristic of the filtered digital series that will be examined for changes indicating the presence of a phase arrival. The CF is operated on by a predictor algorithm which at each sample determines, on the basis of previous values, what the predicted value (PV) of the CF should be at this point. The current value (CV) of the CF is then compared to the PV by taking the ratio CV/PV. If this ratio is greater than some threshold value (THR), a tentative event is declared. Some pickers require the meeting of additional criteria for confirmation of an event at this point and some delay additional tests until later.

After an event has been declared, the picker must at each sample point determine whether to continue in the "triggered" mode or to declare the event over, either because of a mistaken pick belatedly recognized, or because a genuine event is now finished. Once a decision has been made, to declare an event over the picker must decide whether the event was a reportable earthquake and, if so, must output the report information.

With this logic structure in mind, let us examine how several pickers implement the steps outlined in Figure 1, turning first to the function generator.

The CF may be as simple as the absolute value of the input series or it may be a quite complex function, depending on the type of signal expected and the performance required of the picker. The performance of the picker will depend very heavily on the CF, so its choice is important. The arrival of a phase is indicated by a change in the frequency content or amplitude, or both, in the seismic time series, and the CF must respond to this change as rapidly as possible and, ideally, should enhance the change. Most operational pickers have used functions shown in Figure 2. The absolute value function $CF(i) = |Y(i)|$ is easy to compute and the most widely used. The Y^2 function $CF(i) = Y(i)^2$ enhances amplitude changes but not frequency changes. Swindell and Snell (1977) reported the use of the Y^2 function in their investigation of pickers but it has not been widely used. Allen's (1978) function is defined as $CF(i) = Y(i)^2 + K(Y(i) - Y(i-1))^2$, where K is a weighting constant that varies with sample rate and station noise characteristics. For a sample rate of 100 sec, K is usually set at 3. This function was designed to enhance changes in both amplitude and frequency, although at the cost of extra multiplications which require significantly more computing time than the absolute value function, and in some applications might render it impractical.

Although the absolute value function is not so responsive as some functions to changes in the input, it has been used by many successful picker algorithms, including those of Ambuter and Solomon (1974) in an analog form, Anderson (1978), Matsumura *et al.* (1981), and McEvilly and Majer (1982). An important advantage of this function is its ease of computation, an attribute whose importance is often overlooked by those accustomed to running offline jobs on large main frame computers. In many applications of automatic pickers, they must run in low-power, field-operated microcomputers of very limited computing power as in the case of the ASP system of McEvilly and Majer, or if the picker is to be run in a laboratory environment it is advantageous to process as many channels as possible on a minicomputer, which may easily be overloaded. Stewart's (1977) system, for example, strained to the limit its host computer in processing 112 channels.

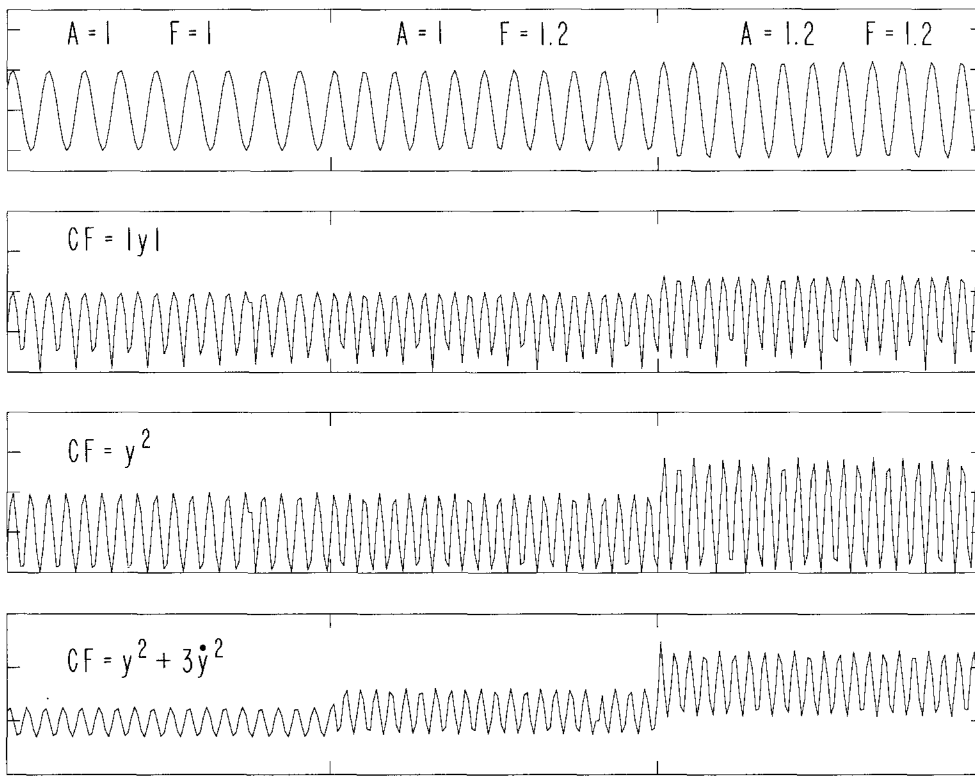

FIG. 2. Response of three commonly used CFs to changes in an input signal. *Top trace* is input sinusoid composed of three sections with relative amplitudes and frequencies varied by 20 per cent as labeled. *Lower three traces* are the responses of the CFs.

Stewart's (1977) function is an example of a CF rather different from those we have seen. Stewart (1977, p. 439) referred to his CF as $MDX(k)$ and described it as follows

> The first step in the transformation process *** is to compute the simple first difference of the incoming signal ($DX_k = X_k - X_{k-1}$, where k represents the current time epoch). The sign of the current first difference DX_k is compared to the sign of the previous first difference DX_{k-1}. If the signs are the same, and if this sign has persisted for less than eight consecutive times, then the value of the modified signal MDX_k is taken to be its current value increased by DX_k. Otherwise, the value of the modified signal is taken to be DX_k. This technique transforms the incoming signal in such a way that (1) the oscillatory nature of the signal is preserved, (2) the direction of first motion is preserved, (3) the frequency components of the signal below that for local earthquakes, especially the diurnal and longer term drift, are reduced, and (4) slightly emergent onsets have a chance to be detected.

Stewart's event declaration criterion uses the absolute value of this $MDX(k)$ and thus the function, in a sense, is a combined low-cut filter and absolute-value function. The advantage of Stewart's function is that it is very fast to compute because it involves only add, subtract, and comparison operations. Figure 3 demonstrates the effectiveness of Stewart's function in achieving his objectives.

In examining the CF for indications of a seismic-phase arrival, the picker compares the CV against the PV. The PV is the maximum expected value of the CF in the absence of a phase arrival. The maximum value is predicted on the basis of the immediate history of the CF. The PV is usually taken as some form of the average absolute value of the function, with the exact form of average depending on the particular algorithm used. Matsumura and Hamada (1976) used σ, the standard deviation of the seismic-input series averaged over some time. McEvilly and Majer (1982) first removed the mean from the input series and then calculated the mean deviation of the resulting series over short and long window lengths. The longer window length mean deviation provides the PV used in threshold calculations.

Allen (1978) calculated for PV a long-term average (LTA) of the CF by use of a low-pass digital recursive filter.

$$PV(i) = (1 - K)(PV(i - 1) + K(CF(i))$$

where the filter constant K, is a number between 0 and 1.

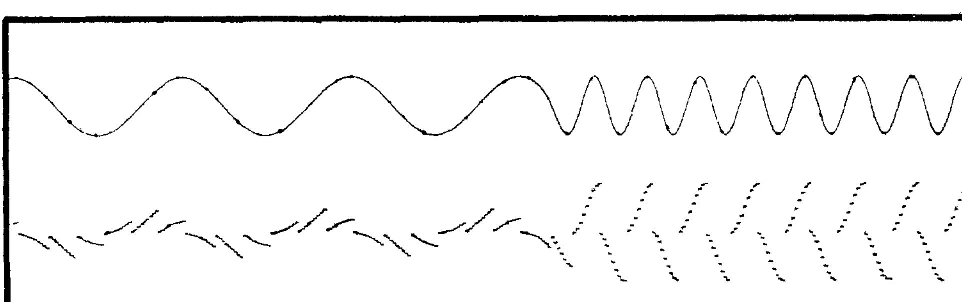

FIG. 3. Stewart's (1977) CF before taking absolute value, showing high-frequency enhancement. Frequencies are 1 and 3 Hz (after Stewart, 1977).

The CV of the CF may be the unchanged value of the $CF(i)$ at the current sample, or it too may be an average of the past sample history, but with much shorter averaging time. The short-term average (STA) that is used as the CV can be set to a time constant or averaging time as short as 2 or 3 samples to insure very rapid response to changes in the CF and thereby aid in accurate timing; or it may be set to a somewhat longer average window to help ignore very short spikes and "glitches." All these averaging algorithms are quite similar in their behavior, and their computed averages will differ only by a constant factor when dealing with noise of constant spectral distribution. Amplitude changes on a time scale short compared to the effective averaging time will result in little change in the average; on a scale comparable to or longer than the averaging time will result in a changed average.

The detection operation consists of comparing the CV with the PV, and if their ratio CV/PV is greater than some THR, an event is declared. Therefore, the criterion for event declaration is that

$$CV > PV \times THR.$$

By using two averages in this way, signal changes and thereby algorithm sensitivity are normalized against background noise level. A slowly increasing noise level, from the onset of a windstorm for instance, will gradually increase a 1-min LTA and the PV. This will result in a higher event criterion level, so the picker will not generate an excessive number of false triggers on the wind noise. If the effective time constant of the LTA is decreased further, to 1 sec or less, as in the Allen algorithm as used in the USGS Calnet system, the picker will ignore most vehicular noise. It will also ignore teleseisms and most regional seismic events whose phase arrivals are quite emergent, but in a system aimed at local microearthquakes this is not a significant loss.

Because of the use of short-term and long-term averages in the way described, these algorithms are often referred to as STA-LTA pickers.

The event declaration threshold value, THR, in most pickers is a constant. In the case of Gaussian background noise, this will result in a constant average false trigger interval (FTI) which can be easily adjusted by adjusting THR. If the noise is not Gaussian, however, and especially if its spectral content varies with time, the FTI may change radically. A particularly difficult and also very common example is the short-duration line spikes that occur so often in telephone telemetry signals. Since these are of very short durations, they have almost no effect on the LTA, which is supposed to guard against excessive false triggers from background noise.

In the USGS picker, I have incorporated a dynamic adjustment to vary THR. This value is varied over the range of 2 to 32 to keep the FTI at about 30 sec. This has proved quite effective in compensating for normally occurring changes in noise, especially from telephone line noise. The usual range of operation for THR is from about 4 to about 7. Daily monitoring of this number also gives an indication of line noise problems on stations whose malfunctioning might not otherwise be noticed.

The functions examined here closely represent almost all the CF's in use today. In some cases, a function which at first glance appears quite different is actually very similar to one of these.

Anderson (1978) developed an approach which segments the input series into "blips" which are the individual half-cycle excurisons of the input signal on either side of the mean value of the time series. Each blip is defined by the times of its two zero crossings and its peak, and by the amplitude of this peak. The pick trigger is generated by a blip whose amplitude is greater than the THR, and whose width falls within defined limits. The CF here is simply the absolute value of the input series. The "blip" approach does not alter this, but it has two rather important potential advantages. (1) It requires the use of full processing logic only at zero crossings. At most sample points, the algorithm only looks for a new maximum amplitude and time, and checks for a zero crossing. This economy should significantly lower the average processing time per sample. (2) This approach also allows a kind of pseudo-postprocessing at the time of the pick. The picker could, for example, discard (as telemetry line spikes) initial pulses which are extremely high and narrow or (as another type of instrument noise) those which are too broad. Anderson (1978) described the use of this algorithm in an offline system, but it should be equally useable in online applications, and as shown below, its ability to recognize a mistaken pick very quickly could improve average pick accuracy by a noticeable margin.

After an event has been detected, the picker must then decide when the event is over. This termination decision is closely connected with the validity decision as to whether the event was "valid" and something to be reported, or merely a mistake which should be written off while returning as rapidly as possible to surveillance mode. While the event is in progress, the termination decision will be based on an inspection of the event as it has thus far been observed, and if, after a terminate decision has been made, the event is deemed to be a false trigger, it will be discarded without a report. All of the currently operating pickers incorporate a "bug" or pitfall of the sort described by Anderson (1978, p. 65)

> Suppose a false trigger occurred just before an actual arrival, such that the actual arrival was contained in the inspection interval. If the inspection of the trigger rejected it as a first arrival, as it should, the actual arrival would be thrown away as well, since the entire inspection interval is never considered again.

Anderson's offline system avoided this problem by "backing up" to the false trigger point and starting over from there, an expedient not usually available to presently operating online systems.

An additional closely related bug can occur if, in the example quoted, the algorithm is tricked by the real event into declaring the entire sequence including the false first arrival and the real event to be a single genuine event. The result here will be not a missed phase but one with a spuriously early arrival time. In the USGS Calnet system using the Allen algorithm, this second bug is the more prevalent, and I have tried to minimize its effects in two ways. First, the picker abandons a false pick very quickly, as described in Allen (1978). I estimate that a false pick is usually abandoned within about 0.3 sec after initiation. To maintain an acceptably low probability of spuriously early picks on valid events, one must adjust other constraints. The probability of an early pick $P(EP)$ may be written as

$$P(EP) = \frac{D}{FTI}$$

where D is the expected duration of a false pick and FTI is the interval between false triggers. Since the dynamic threshold adjustment sets FTI at 30 sec, and D is about 0.3 sec. This leads to a probability of about 0.01 that a given pick will be early, which was judged acceptably low. A different probability may be set by an appropriate setting of FTI or modification of the algorithm to change D.

The algorithm for determining when an event is over will depend to a great extent on the overall objectives of the picker. In the currently operating version of the Allen (1978) algorithm as used in the USGS Calnet system, the magnitude of an earthquake is determined from the coda length by a method similar to that of Lee *et al.* (1972). The goal was to make coda lengths as reported by the automatic system conform to values reported by analysts working with film records of the same traces. The analyst measures the coda length extending from onset until the coda amplitude falls below 1 cm as measured on the film projection screen used in hand analysis. The picker algorithm measures until the absolute value of the seismic amplitude falls below 125 mV (corresponding to 1 cm on film) for 4 sec, and then subtracts this 4 sec from the total duration. If the noise level at a station is too high to allow this approach, the coda is measured until it subsides below noise level, and the report is flagged as a nonstandard number to be treated with caution in magnitude determination. This has resulted in automatic coda length numbers which agree closely with those from hand analysis.

The problem of event termination is separable into two parts. Immediately after a trigger, the picker must decide whether this is a false trigger or whether it still looks like a genuine event. As shown above, delay in making this decision will affect the probability of an early pick, and thereby the overall system timing accuracy. As time goes on it becomes more likely that the trigger is on a real event, so the emphasis shifts to deciding how long the event should be observed before declaring it over and resuming search for another event. In the USGS Calnet system, the "continue or no?" decision is made at each zero crossing for the first part of an event. This algorithm, which is exactly that described by Allen (1978) for the first 3 sec of an event, has proved to be very effective and operates as follows.

After a trigger, the picker continues to carry the STA, and also calculates a continuation-criterion level CCRT which at the trigger is set slightly below the level of STA required for the trigger. This value is then increased slowly as the event progresses. At each zero crossing, the present value of STA is compared with that of the CCRT. If STA $<$ CCRT, the small count register S is incremented by 1; if STA $>$ CCRT, S is reset to 0. Therefore, S always contains the number of consecutive zero crossings that have occurred at which STA $>$ CCRT. An event is declared over when some number of zero crossings with STA $<$ CCRT have occurred. This termination number L will be small (typically 3) at the start of an event to enable the program quickly to reject noise spikes or other very short-term interference. As the algorithm gets into an event, however, L must be larger to ensure that an earthquake observation is not terminated too early during a quiet period. Thus, L is varied as

$$L = 3 + M/3$$

where M is the current number of observed peaks in an event.

After 3 sec the event is tentatively assumed to be real, and the cutoff criterion shifts to the coda amplitude system. This may seem a needlessly complicated algorithm, but as shown above, it is very important to have a strong reset system to preserve pick accuracy.

In an earlier version, this initial approach was carried on through the entire event. The advantage of this approach was the ability to terminate the observation of an event sooner, report it, and return to the job of looking for subsequent arrivals which might be detected in the trailing coda of the previous event. The method was quite successful, but the need for an accurate coda length for magnitude estimates was more urgent, so the present system was adopted.

Stewart's (1977) system held on to a trigger for 0.5 sec in each case and then examined it for frequency, amplitude, and signal-to-noise ratio which could qualify the trigger as a real event. If these criteria were passed, the system entered a coda processing mode in which coda duration, maximum amplitude, and approximate average frequency were determined. If the criteria were not met, the surveillance mode was immediately resumed. Swindell and Snell (1977) used a reset system which declared an event over when the coda energy had decayed below the trigger threshold, but did not reset the system for continued operation for approximately 20 sec. Use of such a cutoff system requires that the trigger threshold be rather high; else the false triggers would result in the system being out of action for an appreciable fraction of the time.

Figure 4 illustrates the importance of proper choice of threshold setting and a fast reset algorithm. These illustrations were made with an offline version of the Allen

(1978) picker because I am most familiar with its use and manipulation, but the principles illustrated are similar for any picker algorithm. The seismic trace is chosen to represent the more difficult types of events that a picker must deal with: a short-weak event and a larger one with a broad emergent first pulse.

In *trace B*, too low a setting of THR results in a high-false trigger rate, and one of the triggers causes an early pick in the second, larger event.

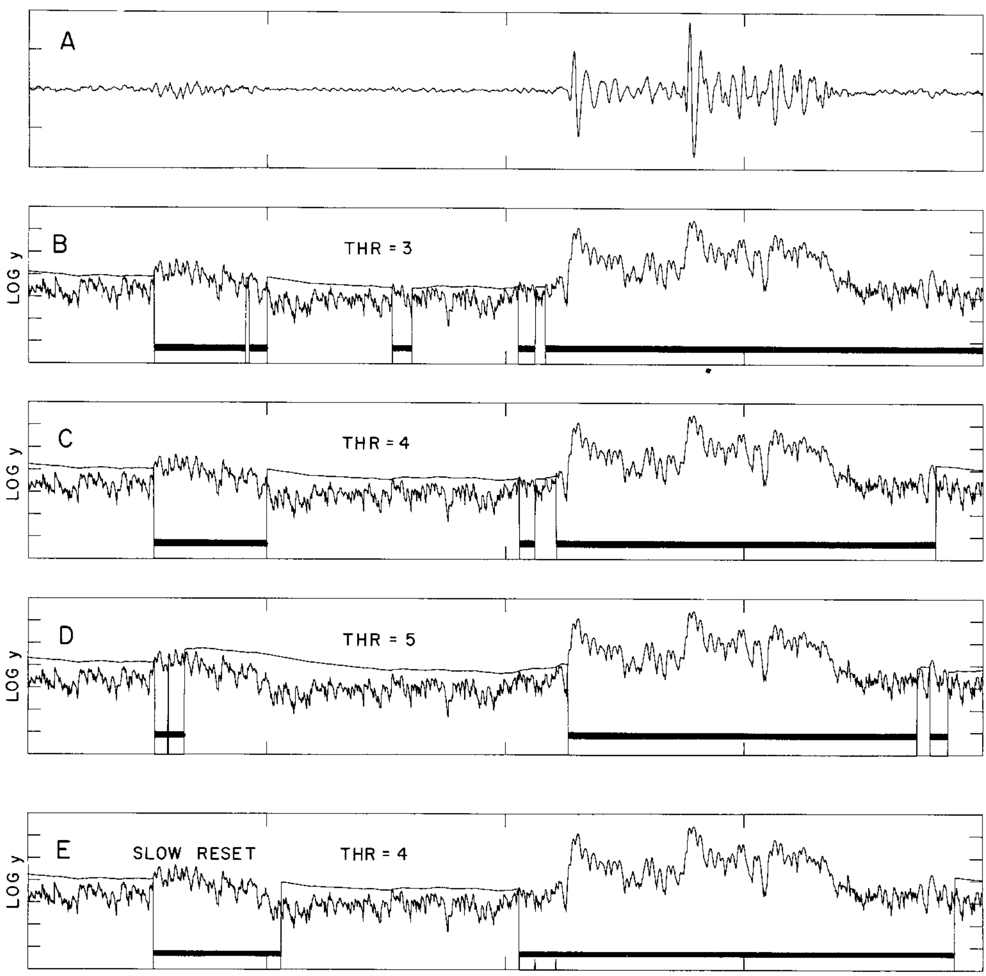

FIG. 4. Picker performance with varying control parameter settings. *Trace A* is the input seismic trace. *Trace B* through *E* show the STA of the CF plotted with the event criterion level, defined as the product of the LTA and the THR. When the STA exceeds the criterion level an event is declared, and the STA is plotted at zero for the duration of the event. The pick will be reported if its duration is greater than 2 sec. *Traces B* through *E* are in arbitrary units, plotted on a logarithmic vertical scale. The heavy bar indicates the time when the picker is in the triggered state. In each trace, the THR is shown. *Traces B* through *D* used fast reset algorithm.

In *trace C*, both events are picked accurately. Note that a false trigger immediately precedes the larger event but is rejected in time to allow accurate picking of the event.

In *trace D*, the threshold is set too high. In the weak event, although the algorithm was triggered, the pick was not above threshold long enough to result in a reported pick. In the second event, the emergent first arrival was missed entirely, and the pick is made on the following stronger peak.

In *trace E*, the threshold is set properly but the algorithm for early release of a false pick has been weakened, resulting in a drastically early pick for the second event.

These plots are intended to illustrate the care which must be exercised in selecting operating parameters and the desirability of incorporating self-adjusting features to compensate for variations in signals encountered.

Algorithms for picking S phase rather than P-phase arrivals are quite rare. McEvilly and Majer (1982) have incorporated one in their ASP system and report good results. It is similar to the P-phase picker of the ASP, but in effect uses a new LTA set after the detected P arrival. When the STA exceeds the new LTA, an S-phase arrival is declared. Since many S arrivals are not clearly marked by large amplitude change, the S picks will not be as consistently reliable as their P-phase analogs, but even a few S picks can be extremely valuable in many cases. Figure 5 shows the pick results of McEvilly and Majer's ASP system.

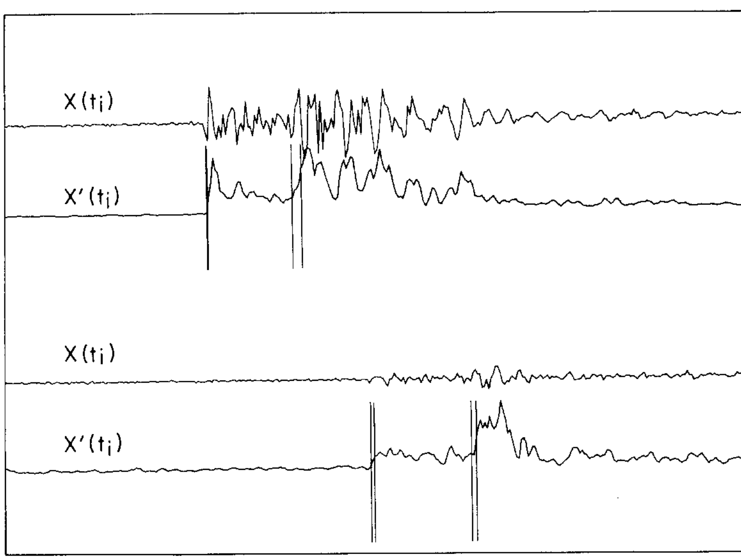

FIG. 5. Examples of P- and S-wave detection and subsequent timing correction in ASP system of McEvilly and Majer (1982). *Right-hand line* of each pair is detection point and *left-hand line* is corrected timing point. *Upper traces* $X(ti)$ are original data, *lower* $X(ti)$ are the filtered CF (after McEvilly and Majer, 1982, Figure 3).

Postprocessing

After an event has been declared over by the picker, it must decide to report the results or decide that the event was not an earthquake and ignore it. This postprocessing can take two forms depending on the particular system. (1) If the picker is operating in isolation without communication with other seismic channels, it will have to make the decision entirely on the basis of the perceived characteristics of the single signal it has observed. (2) If it is a part of a central monitoring system, then the much more powerful tools of an association algorithm will be available. A proper discussion of associators is beyond the scope of this report. Briefly, however, an associator is an algorithm for examining a collection of seismic phase arrivals and detecting an association in space and time among some members of the collection that indicates an earthquake. The power of an associator versus a single-trace evaluation of an event will readily be appreciated by any one who has scanned film records or other multiple-trace records of seismic events. Even small events with weak arrivals, any of which in isolation might be taken for a noise burst, are easily picked out visually as earthquakes because of their association on the record.

Very little has been published on postprocessing verification analysis from single picks. Stewart (1977) listed three requirements for validation of a tentative pick: (1) it must be of sufficiently long duration; (2) it must be oscillatory, not merely a series of unipolar pulses; and (3) the dominant coda frequency must be greater than some lower bound. Allen (1977) described postprocessing routines to measure dominant frequency and the coda shape. The frequency measurements were made on zero-crossing time information stored during the event and relied chiefly on measuring how monochromatic was the signal. Noise, especially motor traffic or wind in trees, tends to have less frequency variation than seismic signals. True frequency domain techniques would be much more powerful. The coda shape was quantified in terms of the relative steepness of the increasing and decreasing portions of the coda envelope. Earthquakes tend to have steeper onsets than decays, but this distinction technique is far from definitive.

McEvilly and Majer (1982) in their ASP system use an associator approach to postprocessing because their system was designed specifically as a network processor, but their final output, the report of a seismic station event, includes a spectral analysis based on a 512-point Fast Fourier transform. In an isolated processor, the result could be used as a noise discriminant.

A picker deals with many "events" which may be either earthquakes or noise bursts. After assessment on the basis of whatever criteria with which it has been provided, an algorithm will have calculated (at least implicitly) a probability $P(E)$ that the event is an earthquake. For a large number of events, there will be a continuum of values from $P(E) \simeq 0$ to $P(E) \simeq 1$. The decision is straightforward in cases where $P(E) \simeq 0$ or $P(E) \simeq 1$ but for the doubtful cases one must decide whether it is more serious to miss a genuine event or to report a nonevent.

In a central network operation such as the USGS Calnet system, the picker for an individual channel may report almost all events of longer duration than about 3 sec. The only additional criteria are the length of the first pulse of the event and perhaps some requirement for minimum dominant frequency as determined by zero-crossing times for the first 100 crossings. In this case, it is of essentially no consequence if a false report is made, because such a report will almost always be caught by the associator program, which can compare this report with results (or nonresults) from neighboring stations. On a typical day for the USGS Calnet system, the 256 operating pickers reported 54580 phase picks to the associator, of which only 413 resulted in phase data included in 44 events. A cursory edit rejected 15 of these events for such reasons as too large a magnitude or too great a depth for the number of stations reporting, leaving 29 probably real events.

Note that at each stage of this process, reports are passed on to the next stage when there is doubt as to their validity, with the tacit assumption that no loss is incurred by delaying the decision to a later stage, at which time additional information will allow more accurate decisions. This strategy could not be followed in a self-contained field picker operating on a single seismometer and recording results for later reports if its recording space or report time were limited. In that case, the acceptance for report of too many false picks could have the serious effect of overloading the report buffer or available reporting time and, thereby, incur the loss of later genuine picks. In situations where these limitations prevail, the fullest use must be made of any available tests of report validity before passing a report on to the next stage.

After a pick has been accepted as valid but before reporting it, some pickers reexamine the timing and refine the exact pick time. Matsumura *et al.* (1981) describe a procedure using 512 sample points that are centered on the tentative pick point and subdivided into eight 64-point windows. By comparison of the mean values in these windows, a new tentative pick is reached and a new set of eight 32-point windows is defined around this new pick. This iterative process is continued through six stages of ever-narrowing windows to reach the final reported pick time.

McEvilly and Majer (1982) examined the trace immediately preceding the preliminary pick using a lower event declaration threshold and looking for the first time at which the $STA > LTA \times THR2$ where THR2 is the new threshold value. Since $THR2 < THR$, this will always result in an earlier trigger point which is taken as the *P* arrival.

Before reporting a valid event, one final postprocessing operation is desirable; the assignment of a reliability weight or confidence factor to the timing. This weight is used by the locator program in determining the importance of that particular pick in least-squares adjustment of the iterative calculations. A reasonable weight assignment is required for proper locator operation, which, after all, is the final result of all this automatic picking. The weight estimate must be fairly accurate, not merely conservative, because the assigned weight of each pick will be compared by the locator against those of other picks in the phase list of an earthquake. A conservative weighting of all picks simply means that they all are accorded approximately equal importance. Therefore, if a pick is good, it must be so indicated.

In the USGS Calnet operation, a weight from 0 (very good pick) to 3 (very poor pick) is assigned on the basis of the noise background as measured by the LTA, the absolute amplitude of the first three peaks of the arrival, and the absolute value of the first difference at arrival. The weighting algorithm rates as reliable those picks with impulsive arrivals as measured by high ratios of pick value to noise level and whose first difference at detection is high. The algorithm now used was arrived at by "cut and try" methods until the automatic weights seemed reasonable when checked by humans. The exact form of such an algorithm will vary with application but the general approach seems sound. Matsumura and Hamada (1976) described a similar weighting system using LTA at pick time and the average amplitude of the first second of signal after the pick.

Evaluation of Results

Evaluation of picker performance using direct comparison of automatic picks and hand picks for a reasonably large data base have been carried out on only a few systems. Stewart (1977), Reasenberg (1980), and McEvilly and Majer (1982) reported evaluations of the Stewart's (1977) system, the USGS Calnet system, and the ASP system.

Stewart (1977) compared his automatic locations with locations made from hand picks. Figure 6 demonstrates that his automatic pick locations for 107 events differed from Calnet locations by less than 1 km in about 82 per cent of the events and by less than 2 km in 92 per cent of the events. Since the set of stations reporting each event was not always identical between hand and automatic picks, and since the locator program and model were not the same, these comparisons are not directly applicable, but they indicate that the automatic results are very close to hand picks.

McEvilly and Majer (1982) similarly compared locator output of their ASP system with output of the USGS Calnet system. They have concluded that the automatic system is at least as effective as an analyst, and comparison of the rms residuals of the locator output indicates that the automatic system may even be superior.

Reasenberg (1980) carried out a detailed comparison of individual pick times between the Calnet handpicks (made routinely from film), handpicks made from digitized records digitized at 100 samples/sec, and displayed on an interactive Cathode ray tube (CRT) and automatic picks from the USGS Calnet system. The CRT times are believed to be the most reliable pick times available because of their high resolution and the ability to "blow up" a section of the record at the arrival, and to zero in carefully on the exact first break time. Figures 7 through 9 summarize Reasenberg's results.

The tighter grouping between the automatic picks and CRT in comparison with the automatic picks and hand picks indicates a clear superiority of automatic picks over hand picks in this data set. The general acceptability of automatic picks can be gauged by the fact that at present, about 40 per cent of all phases reported in the USGS Calnet catalog are automatic picks. This proportion is rising as we learn more about the picker and how to assess and use its results.

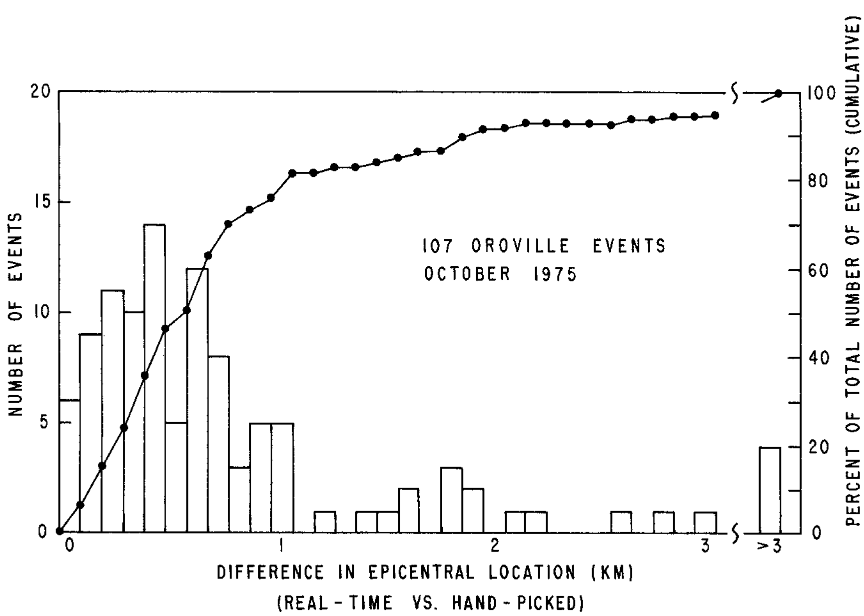

FIG. 6. Difference in epicentral location (in kilometers) between epicentral coordinates determined online and those determined by hand-timing methods. The solid line represents cumulative percentage of the total number of events with epicentral location differences less than the specified distance (after Stewart, 1977, Figure 9).

In estimating the success of automatic pickers versus humans, one must bear in mind that the usefulness of a picker will depend on the exact purpose of the seismic net being processed.

When a relatively small number of readings are to be made, and especially when they are made from digital records on a CRT, the trained analyst will be superior in most cases because of the wider experience and judgment he can bring to bear in marginal cases.

An automatic system can do a better job of phase picking in many cases in a network operation and especially when the hand picks would be made from film. Sources of error in film include galvanometer misalignment, differential stretch of the film, misalignments of the optics in both camera and projector, and operator mistakes. Routine scanning and measurement of seismic network films is not among the more interesting jobs available, and boredom encourages mistakes. When more

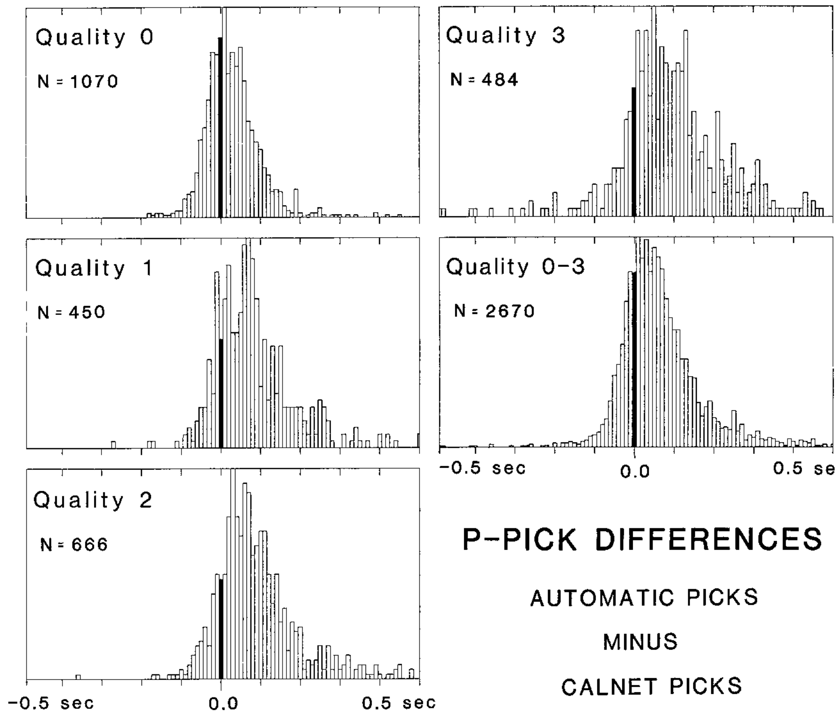

FIG. 7. Timing comparison between automatic and hand picks made from film. Results separated by quality rating as assigned by automatic picker (after Reasenberg, 1980).

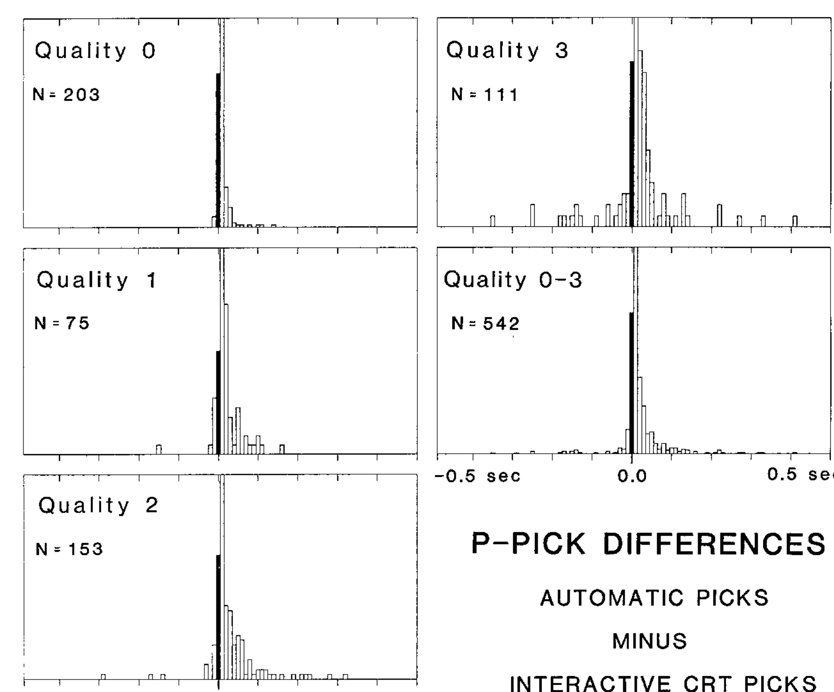

FIG. 8. Timing comparison between automatic picks and hand picks made with CRT. Results separated by quality rating as assigned by automatic picker (after Reasenberg, 1980).

than one operator is involved in timing arrivals, differences in individual practice will result in loss of precision as well as accuracy.

Another advantage of automatic systems is their consistency of performance under varying conditions and over time. A common problem with any network operation is that the magnitude threshold for timed and processed earthquakes will change during periods of high activity such as aftershock swarms. In addition, the subjective element involved in operator decisions will introduce other changes from day to day and month to month, all of which make it difficult to discern subtle changes in seismic activity over a long period. The greater consistency of pick quality in automatic systems even more than any improvement in quality may well be the greatest benefit in automatic network operations.

FUTURE SYSTEMS

Automatic pickers have improved during the last few years to the point where they can now rival human analysts in network operations. During this same time, systems requiring only detection but not timing have improved even further and

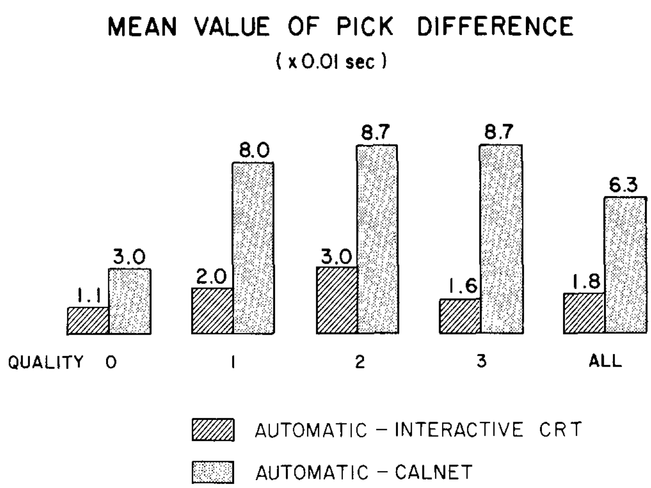

FIG. 9. Comparison of differences between automatic picks and those from film and interactive CRT (after Reasenberg, 1980).

can detect, by frequency-domain techniques, signals of approximately known frequency content in the presence of so much noise that a human analyst would be baffled. The most sensitive of these systems operate in the frequency domain, and although their sensitivity is extremely high, the time required for computation of Fourier transforms has made them unsuitable for general use, especially in large real-time network systems, or in cheaper microprocessor-based systems. This objection can be circumvented by the use of the Walsh transform, which is very similar in use to the Fourier transform but has the important difference that Walsh functions replace the sines and cosines in the Fourier transform. The Walsh functions are generated by logical comparisons, not arithmetic operations, and their value is +1 or −1, so they require only a fraction of the computing time required by Fourier techniques.

Among those reporting the use of Walsh transforms for seismic applications have been Chen (1972), Båth and Burman (1972), Lintz (1973), and Kennett (1974). More recently, Goforth and Herrin (1981) described a very successful detection algorithm using Walsh transforms which runs on a microcomputer. They have demonstrated that the frequency-domain approach is now a practical possibility for online systems and need not be prohibitively time-consuming even with hardware now available.

In conclusion, I will point out what I believe to be a fruitful line of attack if one were to start afresh to design an automatic picker system. The system should have two clearly separated functions: phase detection and phase timing, carried out by separate algorithms. The detection of earthquake energy can best be done in the frequency domain by Walsh transform techniques similar to those used by Goforth and Herrin (1981). On detection of an event, the program would load a working buffer with data samples for a time sequence beginning several seconds before the event and extending several seconds into the event. When this buffer has been filled, the algorithm would begin processing the data to determine the exact arrival time. This algorithm would be a background program operating between samples in the time not used for the ordinary processing of each sample as it arrives. Thus, it would be a sort of pseudo-offline processor which would not be subject to the usual "never look back" constraints of most current pickers. It would have both the superior detection capability of the frequency-domain technique and the precise timing of the time-domain. Presumably, the detector would sometimes detect signals of such low signal-to-noise ratio that the picker could not distinguish them at all, but in general the picker's controlling parameters could be set for very high sensitivity with the assumption that it would almost immediately encounter a seismic signal, not a noise burst. The output from such a detector/picker would contain at least the information incorporated in a normal phase card, and if required, the entire trace could be written from the delay buffer or from the processing buffer to a recording device. This system could be packaged as an independently operating field unit that would be placed at the seismometer location and thus have access to data of bandwidth and dynamic range such as has seldom been available to seismologists. The recording buffer, probably magnetic tape, could be relayed periodically by relatively short telemetry contact to a central collection point. In a large network, the stations might be linked by telephone lines and interrogated daily rather than using dedicated lines to each station.

Alternatively, the detector/picker could be used to process an entire net at a central collection point in an operation similar to those now carried out by McEvilly and Majer's (1982) ASP system or the USGS Calnet system, with the additional possibility of saving the entire trace as well as only descriptors, as at present.

Although choice of hardware would be determined by whether the system was intended as a field system or as an office installation, most of the choices are straightforward and predictable. In either case, the algorithms would be implemented in microcomputers, and the choice of processor and support hardware would be determined mostly by power supply constraints for battery operation in the field units, and by computational requirements in a central-collection-point environment.

The use of microcomputers is required in field equipment to conserve power. McEvilly and Majer's ASP system was implemented with low-power CMOS (Complementary Metal Oxide Semiconductor) microprocessors and the USGS Galnet system uses processors which were selected partly because a low power I^2L (Integrated Injection Logic) version of the processor is available if a battery-operated version ever should be required. Both of these systems were designed several years ago and a larger selection of suitable low-power equipment is available today.

In a central office system, microprocessors are desirable for a different reason. By spreading the computational power of the system through several central processing units (CPUs), the system can be tailored for individual networks, whether they are small ones of half a dozen stations or nets like the USGS Calnet system with several hundred telemetered seismometers. In McEvilly and Majer's (1982) ASP system using 8-bit CMOS processors, each seismic channel is monitored by one microprocessor. In the USGS system, because of the use of faster 16-bit CPUs and a different algorithm, each microprocessor handles eight seismic channels. Both systems employ a "boss" or "supervisor" algorithm running in a separate CPU, plus as many picker CPUs as are required to process the total number of stations in the net. This approach can afford important economies in equipping small nets of from a few to a few dozen stations. Hardware costs are estimated by McEvilly and Majer (1982) at about $2500 per station for the ASP system, and costs for the USGS Calnet system in the current central office configuration are about $500 per station. The fact that only the amount of hardware computing power needed for the specific application must be purchased is the main advantage of distributed processing. It should be emphasized that this proposed system is not based on "pie-in-the-sky" predictions of equipment development to come; the hardware to implement such a system can be purchased today, and it is not considered exotic or even unusual in the electronics business.

For the person intending to build a supersystem, the next step is to define precise objectives for the system: should it save the entire seismic record or only descriptors, what magnitude threshold is required, etc. These objectives will dictate the features to be incorporated in hardware design and the accompanying software. The systems considered here have taken various approaches which can be extended and improved in producing the next generation of automatic phase pickers. Building these machines will be a rewarding challenge in itself, but even more importantly, they can help to make a real and fundamental improvement in the scientific value of the seismic nets they will serve.

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