EVALUATION OF A RECTILINEAR
MOTION DETECTOR

by

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Vordiplom, Technische Universität Munich, 1964

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Geophysics

We accept this thesis as conforming to
the required standard

University of British Columbia
April, 1969
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Date April 28, 1969
One criterion for distinguishing underground nuclear explosions from earthquakes is that most earthquakes occur at considerably larger depths. Focal depth can be determined with seismograms if both the P and the pP arrival are clearly distinguishable.

"REMODE 5A" (REctilinear MOtion DEtector), a time-varying polarization filter for the detection of P-type motion, is applied to artificial inputs and earthquakes. It is investigated how variation of the filter parameters affects the output.

The length of the time window within which the cross-correlation filter operator is calculated must not be small compared to the signal period, especially if the onset of a quake is to be enhanced. If the window is very short, the filter outputs will be erratic. It makes little difference whether the truncated filter operator is tapered at the ends or not.

REMODE 5A removes background noise and much of the signal-generated noise, but its efficiency in picking pP from complicated P coda is not significantly different from more elementary versions of REMODE filters.
Through choice of parameters, REMODE 5A can be made arbitrarily selective to the degree of rectilinearity and the incident angle of signal and noise. However, since the sought-for pP and P will often be contaminated by signal-generated noise, too highly selective a filter may easily reject signal.
TABLE OF CONTENTS

CHAPTER I  INTRODUCTION

1-1 Problem and Background 1
1-2 REMODE Filters Against Frequency Band Filters 4
1-3 Reference to Previous Publications 6
1-4 Aim, Outline, and Scope of This Study 8

CHAPTER II  REMODE FILTERING

2-1 Filter Input from Rotated Seismograms 9
2-2 Cross-Correlation, the Basis of REMODE 11
2-3 Normalized REMODE Filters 13
2-4 "A" Modification to Suppress SV 15
2-5 "REMODE 5A", a Higher Order Filter 17
2-6 Directional Properties 19

CHAPTER III  TESTING TECHNIQUES

3-1 REMODE 5A Parameters 22
3-2 Purpose and Procedure of Testing 25
3-3 Filter Inputs as Employed for Testing 26

CHAPTER IV  RESULTS OF TESTS WITH REMODE PARAMETERS

4-1 Directional Properties : INTANG 29
4-2 Directional Properties : M 37
4-3 Tapering the Edges of the Filter Operator 45
### IV

<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>4-4</td>
<td>Normalization: Summation Limits</td>
<td>53</td>
</tr>
<tr>
<td>4-5</td>
<td>Time Window and Number of Lags</td>
<td>56</td>
</tr>
<tr>
<td>4-6</td>
<td>Number of Convolutions</td>
<td>62</td>
</tr>
</tbody>
</table>

#### CHAPTER V SUMMARY AND CONCLUSIONS

<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>5-1</td>
<td>Summary</td>
<td>68</td>
</tr>
<tr>
<td>5-2</td>
<td>Conclusions</td>
<td>71</td>
</tr>
</tbody>
</table>

### REFERENCES

<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>REFERENCES</td>
<td>72</td>
</tr>
</tbody>
</table>
LIST OF FIGURES

FIGURE 1 Schematic illustration of P and pP travel paths. 2
FIGURE 2 Orientation of the P ray towards the seismogram coordinate system after rotations. 10
FIGURE 3 Detection of P and SV motion by product of R and Z component of motion (after Basham, 1967). 16
FIGURE 4 Half-cycle cosine function illustrating approximate response of normalized REMODE processors (after Basham, 1967). 18
FIGURE 5 An example of an artificial filter input consisting of three sinusoidal segments. 27
FIGURES 6 THROUGH 11 An example of the effect of varying the specified angle of incidence INTANG.
FIGURE 6 Filter input for the outputs shown in Figures 7 through 11. 31
FIGURE 7 Output for INTANG=15°. 32
FIGURE 8 Output for INTANG=40°. 33
FIGURE 9 Output for INTANG=45°. 34
FIGURE 10 Output for INTANG=50°. 35
FIGURE 11 Output for INTANG=75°. 36
FIGURES 12 THROUGH 16 An example of the effect of varying the cosine power M governing directional discrimination.
FIGURE 12 Filter input for the outputs shown in Figures 13 through 16. 38
FIGURE 13 Output for M=0, and no convolution. 39
FIGURE 14 Output for M=3, and no convolution. 40
FIGURE 15 Output for $M=0$, and 3 convolutions. 41
FIGURE 16 Output for $M=3$, and 3 convolutions. 42
FIGURE 17 Schematic representation of $\cos^M(\text{INTANG} - \text{BETA})$ (after Griffin, 1966a). 44
FIGURES 18 THROUGH 24 46
Examples of the effect of different types of tapering.
FIGURE 18 Filter input for the outputs shown in Figures 19 through 24. 46
FIGURE 19 Output for NO TAPERING, and no convolution 47
FIGURE 20 Output for HAMMING window, and no convolution. 48
FIGURE 21 Output for DANIELL window, and no convolution. 49
FIGURE 22 Output for NO TAPERING, and 2 convolutions 50
FIGURE 23 Output for HAMMING window, and 2 convolutions. 51
FIGURE 24 Output for DANIELL window, and 2 convolutions. 52
FIGURE 25 Schematic representation of the effects of different types of normalization applied to an input with extremely low noise level. 55
FIGURES 26 THROUGH 29 58
Examples of the effect of varying window width $LW$ and maximum lag $LAGS$.
FIGURE 26 Filter input for the outputs shown in Figures 27 through 29. 58
FIGURE 27 Output for $LW=40$, and $LAGS=24$. 59
FIGURE 28 Output for $LW=20$, and $LAGS=10$. 60
FIGURE 29 Output for $LW=4$, and $LAGS=4$. 61
FIGURES 30 THROUGH 32 64
Examples of the effect of varying the number $NC$ of convolutions.
FIGURE 30 Filter input for the outputs shown in Figures 31 and 32. 64
FIGURE 31 Output $FZ$ for $NC=0$ (31a).
Output $FZ$ for $NC=1$ (31b). 65
FIGURE 32  Output PZ for NC=2  (32a).
Output PZ for NC=3  (32b).
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CHAPTER I

INTRODUCTION

1-1 Problem and Background

Seismic records are always noise-contaminated. Sometimes the noise level is so high that it is impossible to recognize any signal on the record. Fortunately, through filtering one can produce a modified record on which the signal is easier to recognize by increasing the signal-to-noise ratio.

To detect the pP phase and the onset of the P phase on such noise-contaminated record, careful filtering is often needed. If both these phases are discernible one can determine the focal depth of the source from the time elapsed between the two. Accurate knowledge of focal depth is an important clue for deciding, on the basis of seismic records, whether a given event was an earthquake or a nuclear explosion.

The principle of how to determine focal depth from the time elapsed between the arrivals of P and pP is illustrated in Figure 1. The pP is an echo of the
E = Centre of the explosion or earthquake (Focus).
R = Point of reflection at the surface.
S = Seismograph station.

This figure is not drawn to true scale.

Figure 1. Schematic illustration of P and pP travel paths.
P, by reflection at the surface above the source. Imagine the same figure drawn to true scale. Obviously then the path ES is almost identical to AS, and so is ER to AR. Thus, the following approximation will apply, and it will be the more accurate the shallower the source will be: The reflection point is vertically above E, and the time difference between the P and the pP arrivals is the time it takes a compressional wave to travel twice the epicentral depth. I.e., the focal depth is \( h \approx t(pP-P) V/2 \) where \( t(pP-P) \) is the time difference between the arrivals of P and pP, and \( V \) is the average source-to-surface velocity.

More accurate for determining the focal depth \( h \) is the equation

\[
t(pP-P) = \frac{2h}{V \cos \theta} - \left( \frac{dt}{d\Delta} \right) \Delta
\]

where \( \Delta = 2h' \tan \theta \), \( h' \) is a first approximation to \( h \), \( \theta \) is the inclination to the normal of the ray reflecting from the surface, and \( \frac{dt}{d\Delta} \) is the inverse phase velocity of P as a function of \( \Delta \). The inclination angle can be determined from the equation

\[
\sin \theta = V \left( \frac{dt}{d\Delta} \right)
\]

(Basham and Ellis, 1969).

We must understand that the P and the pP can be
buried under noise of two distinctly different kinds, background noise and signal-generated noise.

Background noise is all those vibrations which are picked up and recorded by the seismograph and do not originate from the earthquake or the explosion, but from wind or water waves, or is cultural noise like traffic and construction.

Signal-generated noise is the product of multiple reflections and refractions that take place at the interfaces and inhomogeneities of crustal layers. Most of this originates underneath the station.

The primary P, being the first of all pulses to arrive at the station, will only be affected by background noise and not by the later arriving signal-generated noise.

The problem is to pick the later arriving pP from the P coda. The P coda is formed by the reverberations near the source and the signal-generated noise from the vicinity of the receiver.

1-2 REMODE Filters Against Frequency Band Filters

Digital filters for the computer processing of seismic records can be designed to pass any specified frequency band and to reject, to a greater or less degree,
other frequencies. The spectrum of background noise is often concentrated around frequencies differing from the dominant period of P and pP signals (Basham, 1967, Chapter III). Consequently, frequency band filtering can serve to reduce background noise that contaminates pP and P.

Unfortunately, frequency filtering is not effective in separating the pP from that part of the P coda which is signal-generated noise. This is so because, in principle, there is no frequency difference between P, pP, and the signal-generated noise of the P coda: we remember that the pP as well as the signal-generated noise (SGN) stem from reflections or refractions of the P. Neither reflections nor refractions cause any changes in frequencies.

However, there is one strong point of distinction between pP and SGN that can be exploited for filtering purposes: the motion of pP is rectilinearly polarized, whereas the motion of SGN is likely to be elliptically or randomly polarized. The random or elliptical polarization of the SGN is caused by superposition of many rectilinear components which stem from the multiple reflections and refractions in the crustal layers.

REMODE filters ("REctilinear MOtion DETector") discriminate against signal for which the input motion is not rectilinear along the ray path, but random and elliptical.
When the input motion is predominantly rectilinear large spikes are produced for output. These spikes do not necessarily have the true shape of the input pulses.

Shear waves and compressional waves, i.e. S and P, are both rectilinearly polarized and thus will both be amplified by a REMODE filter. But in S waves, particles move along straight lines perpendicular to the direction of propagation, whereas in P waves the particles move colinearly with the propagation vector. This difference permits one to suppress S and pass P (including pP) by adding to the REMODE filter a relatively simple modification called a "motion product operator". The motion product operator is explained in Chapter II.

REMODE filters are time-varying and thus need far more computer time than the simpler frequency filters which remain unchanged along the record.

1-3 Reference to Previous Publications

The principle of REMODE filters was developed by researchers at Teledyne Industries: Mims and Sax (1965), Griffin (1966a, 1966b), Sax (1966). An account in physical and mathematical terms of how the REMODE process works is given in Chapter II of the present study. At this point it shall only be stated that the mathematical formulation of a REMODE processor contains several parameters. Their
magnitudes can be individually varied to a considerable extent; this allows a wide choice of REMODE types differing in their filtering qualities.

Griffin (1966a) discusses a group of such filters (REMODEs 2, 2A, 3, 3A) of intermediate sensitivity. Based on theoretical considerations he recommends a set of parameter values likely to produce good results in seismic data processing. Basham (1967) applied one of these filters (REMODE 3A), with parameters as suggested by Griffin, to the records of 40 teleseismic events; he detected the phase pP on the records of 25 events, 16 of which had reported depths of less than 40 km.

Griffin (1966b, and 1966a) also suggests a filter discriminating much more strongly than those previous types against frequency components which are not purely rectilinear in their polarization, or which arrive from directions differing from a specified angle of incidence. In order to evaluate the potential of REMODE 5, he performed test-runs with artificial records. The latter were steady state sinusoids under rectilinearly polarized noise. But because this artificial noise was rectilinear, Griffin's results are not an evaluation of how powerful REMODE 5 might be for picking pP from non-rectilinear signal-generated noise.
Aim, Outline, and Scope of This Study

The purpose was to determine how much better than the less sensitive REMODE 3A might REMODE 5A be for detecting pP. Special attention was given to two questions:

(i) Is it worthwhile to have the filter very sensitive? (Higher sensitivity requires more computer time).

(ii) Which parameter values are a good compromise between the power of discrimination against non-rectilinear motion and computational expense?

Chapter II presents in a condensed form the mathematical principles underlying REMODE filtering in general, and in particular the highly specialized REMODE 5A.

In order to answer questions (i) and (ii), varying modifications of REMODE 5A were applied to test inputs.

Chapter III outlines testing techniques. The resulting filter outputs are plotted and discussed in Chapter IV.

Summary and conclusions constitute Chapter V.
CHAPTER II

REMODE FILTERING

Since the mathematics of REMODE have been discussed in previous publications, (Griffin 1966a and 1966b, Basham 1967), only a brief account will be given here.

2-1 Filter Input from Rotated Seismograms

REMODE filters are two-dimensional: two input traces and two output traces. The input is the representation by two perpendicular components, R and Z, of the wave motion incident at the station. R and Z are in the vertical plane through the incident ray, and the ray is the bisector between the two (Figure 2). For a seismic ray arriving at the station from any direction this R,Z representation can be obtained from a three-component seismogram by two successive rotations of the coordinate system. The R,Z bisector is rotated into the apparent direction of incidence which is determined by fitting a straight line to the vertical-radial particle motion. (For details see Basham, 1967).
Figure 2. Orientation of the P ray towards the seismogram coordinate system after rotations.
Assuming that the layering of the crust underneath the station is horizontal, the boundary conditions at the interfaces require that, in theory, only P-type and SV-type motion will be generated as a result of multiple reflections and refractions of an incident compressional wave. All such P and SV motion will be in the vertical plane through the ray and thus will be represented in total by the two components R and Z. Thus, with compressional phases, all available signal energy is utilized. In practice, some scattered SH energy will also be present and record on the three-component seismogram. But it will not show on either of the two REMODE input traces because the R-Z plane is perpendicular to such SH motion. Actually a side effect of the seismogram rotations, this suppression of SH is desirable when one wishes to apply REMODE to the detection of pP and P.

2-2 Cross-Correlation, the Basis of REMODE

The even part of the cross-correlation function \( c(T) \) between \( R(t) \) and \( Z(t) \) is large compared to the odd part when the polarization of motion in the R-Z plane is predominantly rectilinear; and vice versa, when motion of elliptical and random polarization prevails, the even part of \( c(T) \) is small relative to the odd part (Griffin, 1966a, Basham, 1967). Consequently, if we convolve (i.e., use as a filter operator) this even part of \( c(T) \) with the
input \( R(t), Z(t) \), the output will be large only where the particle motion is predominantly rectilinear (e.g., P, pP, SV). Elliptical motion will be suppressed.

With various seismic phases arriving at different times \( t \), the type of polarization and so the relative magnitude of the even part of \( c(T) \) will vary with time. In order to have large output only from the rectilinear phases, a time-varying filter is required. The filter operator \( c(T) \) is calculated anew at every point \( t \) within a segment (or "time window") \( LW \) around \( t \):

\[
(1) \quad c(+T) = \sum_{t-LW/2}^{t+LW/2} Z(t)R(t+T)
\]

Instead of extracting the even part from \( c(T) \) we use a simpler technique which was demonstrated (Griffin 1966a, Basham 1967) to result in a satisfactory filter function: \( c(T) \) is computed for positive lags \(+T\), and then an even function is generated by reflecting \( c(+T) \) at the origin according to

\[
(2) \quad c(-T) = c(+T)
\]

Because of this symmetry, REMODE filters are phase distortionless.

The largest lag \( T_{\text{max}} \) for which \( c(T) \) is calcu-
lated must be smaller than the window length $LW$ since for larger lags either $R$ or $Z$ would contribute to the cross-correlation with terms which are outside the interval $LW$ around the point $t$ for which the particular filter operator $c(T)$ applies. Griffin (1966a) recommends to keep $T_{\text{max}} = LW/2$ in order to retain within the sum (1) significant portions of the record segment centered on $t$ for both $R(t)$ and $Z(t)$.

The filter output $FR(t), FZ(t)$ is computed according to

$$FR(t) = \sum_{T=-LAGS}^{T=+LAGS} R(t-T) c(T)$$

$$FZ(t) = \sum_{T=-LAGS}^{T=+LAGS} Z(t-T) c(T)$$

The filter operator $c(T)$ is a different function for every data point $t$. For this reason, REMODE processing requires much more computer time than frequency band filters which apply the same operator along the entire record.

2-3 Normalized REMODE Filters

The output of the filter described in Section 2-2
will depend on the amplitudes of $R$ and $Z$ as well as on the degree of rectilinearity of the motion. In practical applications (e.g. picking pP) one may wish to discriminate only by rectilinearity and not by amplitudes. Then, large-amplitude non-rectilinear noise camouflaging a small-amplitude pP could be suppressed and the (rectilinear) pP detected.

This feature is realized through multiplying the unnormalized output by normalization factors $X_{\text{NORM}}(t)$.

\[
FR(t) = FR(t) \cdot X_{\text{NORM}}(t) \\
FZ(t) = FZ(t) \cdot X_{\text{NORM}}(t)
\]

$(X_{\text{NORM}}(t))^2$ are approximately proportional to the reciprocals of signal energy averaged over the time windows $LW$ within which the cross-correlation filter functions are computed:

\[
(X_{\text{NORM}}(t))^2 = \frac{1}{\sqrt{\sum_{t-LW/2}^{t+LW/2} R^2(t) \cdot \sum_{t-LW/2}^{t+LW/2} Z^2(t)}}
\]

Disadvantages of normalization are that scattered pulses (SGN) of weak amplitude but high degree of rectilinearity may be unduly enhanced, and the original shapes of pulses are not likely to be preserved.
2-4 "A" Modification to Suppress SV

SV, being rectilinear, will pass through an unmodified REMODE equally well as P and pP. The modification "A" (so designated by Griffin) exploits the fact that SV motion is perpendicular to the ray, whereas compressional P particle motion is along the ray. The product $R(t)Z(t)$ is $>0$ when the motion at $t$ is compressional, and $<0$ for SV; Figure 3 (adopted from Basham, 1967). In order to suppress SV a simple "motion product operator" might thus be used:

\[ \text{FR}_A(t) = \text{FR}(t) \quad \text{for } R(t)Z(t) \geq 0 \]
\[ \text{FZ}_A(t) = \text{FZ}(t) \]

\[ \text{FR}_A(t) = 0 \quad \text{for } R(t)Z(t) \leq 0 \]
\[ \text{FZ}_A(t) = 0 \]

Instead of the motion product $R(t)Z(t)$ of a single point $t$, in practice we use the zero-lag cross-correlation calculated within the usual time window $\text{LW}$:

\[ \text{FR}_A(t) = \text{FR}(t) \quad \text{for } c(0) = \sum_{t-\text{LW}/2}^{t+\text{LW}/2} R(t)Z(t) \geq 0 \]
\[ \text{FZ}_A(t) = \text{FZ}(t) \]

\[ \text{FR}_A(t) = 0 \quad \text{for } c(0) < 0 \]
\[ \text{FZ}_A(t) = 0 \]
Figure 3. Detection of P and SV motion by product of R and Z component of motion (after Basham, 1967).
The filter could be made to reject \( P, pP \) and pass \( SV \) by simply setting the output zero for \( c(0) \geq 0 \), and vice versa.

2-5 "REMODE 5A", a Higher Order Filter

Griffin (1966a) shows that the response of a normalized A-type REMODE filter can be approximated by a quarter-cycle cosine function (Figure 4). Frequency components \( R(\omega), Z(\omega) \) of the input pass in proportion to the cosine of the phase difference \( \Delta \gamma = (\mathcal{F}_R(\omega) - \mathcal{F}_Z(\omega)) \) between them. This of course means passing rectilinear rather than elliptical motion: \( \Delta \gamma = 0 \), \( \cos \Delta \gamma = 1 \) when the frequency component's motion is purely rectilinear, and \( \Delta \gamma = 90^\circ \), \( \cos \Delta \gamma = 0 \) for circular polarization. Elliptically polarized motion may still come through at appreciable amplitude, e.g. \( 1/2 \) for \( \Delta \gamma = 60^\circ \).

Higher order REMODE filters, like REMODE 5A, discriminate more rigidly against frequency components for which \( \Delta \gamma(\omega) \) is between \( 0^\circ \) and \( 90^\circ \): their response varies as \( \cos^{(NC+1)} \Delta \gamma \) instead of \( \cos(\mathcal{F}_R - \mathcal{F}_Z) \). This narrowing of the "phase window" is achieved by convolving the filter function (i.e. the symmetric cross-correlation) \( c(T) \) with itself in \( NC \) stages (Griffin, 1966b):

\[
(7) \quad (c(T))^{n+1} = (c(T))^n \star (c(T))^n
\]

where \( n = 0, \ldots, NC \)
Figure 4. Half-cycle cosine function illustrating approximate response of normalized REMODE processors (after Basham, 1967).
Truncation to original length $2 T_{\text{max}}$ after each self-convolution is needed because each such convolution doubles the length of the filter operator. Tapering the truncated ends is optional (Section 4-3).

The larger $N_C$ the more sensitive the filter will be against non-rectilinear motion. But every increase in $N_C$ is expensive in computer time since the entire process is carried out for every single point $t$ anew.

### 2-6 Directional Properties

REMODE 5A discriminates, by multiplication with a factor like (8), against input arriving at an apparent angle of incidence $\beta$ whenever $\beta$ differs from a specified direction $\alpha$:

$$\cos^M(|\beta - \alpha|)$$

Any value for $M$ can be chosen, thus allowing the pass range of this directional filter to be as narrow as desired.

$\beta$, the apparent angle of incidence at each point $t$, is found from the input $R,Z$ by

$$\beta = \beta(t) = \tan^{-1}\left(\frac{\sum_{t-LW/2}^{t+LW/2} R^2(t)}{\sum_{t-LW/2}^{t+LW/2} Z^2(t)}\right)$$
Instead of (8) we use (10,11) (Griffin, 1966b), thus including a discrimination against S phases, while the directional characteristics of (8) remain unchanged.

\[
(10). \quad \cos^M(|BETA + ANGINC (2 \text{ REJECR} - 1)|)
\]

where

\[
(11) \quad \text{REJECR} = \begin{cases} 
0 & \text{for P-type input} \\
1 & \text{for S-type input}
\end{cases}
\]

The distinction (11) is made according to the motion product operator (pp 15-17) being positive (P) or negative (S).

The two possible cases for (10) are

\[
(10a) \quad \cos^M(|BETA - ANGINC|) \quad \text{for P}
\]
\[
\text{or}
\]
\[
(10b) \quad \cos^M(|BETA + ANGINC|) \quad \text{for S}
\]

Assuming that the seismogram rotations (p9) placed the bisector between R and Z (i.e. BETA=45°) exactly into the influx direction of seismic energy, we shall specify ANGINC=45°. Then, any phase approaching along the bisectorial ray will be passed with full amplitude if it is of the P type (10a), or totally suppressed if it is S (10b).

Pulses arriving at BETAs not equal to ANGINC, i.e. noise, will be suppressed the more strongly the lar-
ger $M$ is. However, $M$ should not be chosen too large in order to retain $P$ motion of which the BETAs differ only little from ANGINC; for due to scattered energy the BETAs from (9) may oscillate about the average value ANGINC even if the $P$ itself is exactly within the bisectorial ray.
CHAPTER III

TESTING TECHNIQUES

3-1 REMODE 5A Parameters

In the author's REMODE 5A program, the six integer parameters LW, LAGS, NC, M, IFTAP, INTANG (=ANGINC) could be individually adjusted. Each of them would influence the filter characteristics. Their magnitudes were printed out together with the plotted outputs of each test run (Chapter 4).

LW is the length (in data intervals) of the time window within which the cross-correlation c(T) is taken (pl2). Griffin (1966a) points out that the relation of LW to signal duration and period of noise will determine how effectively a REMODE filter will isolate a weak signal. He argues that the window should be short enough to be just filled by the signal being sought because a long window over short and weak signal can sample polarization more representative of noise than of signal and as a consequence the filter might well reject both signal and noise; too short a window, however, might miss part of
a signal.

LAGS is the largest lag $T_{\text{max}}$ for which the cross-correlation $c(T)$ is calculated (pl2f). The length of the filter operator is 2 LAGS.

NC, being either a one or a two digit number, indicates the number NC of convolutions of the filter operator with itself (pp 17, 19) as well as the kind of normalization applied (pl4f). Three types of normalization were tried; they differ in the limits of the sums in formula (5). These limits as determined by the first digit (or by NC being one digit instead of two) are illustrated in the following table.

<table>
<thead>
<tr>
<th>FIRST DIGIT = 1 , or NC ONE DIGIT ONLY</th>
<th>$\sum_{t=LW/2}^{t}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>FIRST DIGIT = 2</td>
<td>$\sum_{t=LW/2}^{t+LW/2}$</td>
</tr>
<tr>
<td>FIRST DIGIT = 3</td>
<td>$\sum_{t}^{t+LW/2}$</td>
</tr>
</tbody>
</table>

The second digit, or NC itself where only one digit, is the actual number of convolutions. Where further on we refer to NC we mean the latter.
LW, LAGS, and NC strongly influence filter response, whereas the remaining three parameters M, IFTAP, INTANG are of lesser significance. This will be illustrated by test results in Chapter 4.

M, we remember, determines the directional properties of the filter (Section 2-6). Possible undesirable consequences of having too large an M were pointed out on p21.

INTANG (=ANGINC) designates in degrees the "specified direction" as explained in Section 2-6.

IFTAP determines the form of tapering which may be applied to the truncated filter operator before it is convolved with the time series. Tapering is carried out by superimposing on the filter operator a multiplicative window of equal length.

<table>
<thead>
<tr>
<th>IFTAP</th>
<th>WINDOW</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>NO TAPERING</td>
</tr>
<tr>
<td>1</td>
<td><img src="LENGTH=2T_%7Bmax%7D" alt="Diagram" /> [D(T) = 1 - \frac{T}{T_{max}}]</td>
</tr>
<tr>
<td>2</td>
<td>&quot;HAMMING&quot; [D(T) = 0.54 + 0.46 \cos\left(\frac{\pi T}{T_{max}}\right)]</td>
</tr>
<tr>
<td>3</td>
<td>&quot;HANNING&quot; [D(T) = 0.50 \left(1 + \cos\left(\frac{\pi T}{T_{max}}\right)\right)]</td>
</tr>
<tr>
<td>4</td>
<td>DANIELL [D(T) = \sin\left(\frac{T}{T_{max}}\right) / \left(T/T_{max}\right)]</td>
</tr>
</tbody>
</table>
The reason for tapering is that the sharp edges of a truncated and untapered time domain filter operator may introduce undesirable GIBBS' oscillations into its frequency response. Tapering those edges strongly reduces GIBBS' oscillations. (A more detailed discussion of tapering is given by Blackman and Tukey (1959).)

3-2 Purpose and Procedure of Testing

The overall goal of this study was to find as efficient as possible a filter which would detect pP and P onsets of earthquakes and explosions. An attempt was made to determine how the filter parameters (Section 3-1) influence its characteristics. The latter were evaluated by applying REMODE 5A to selected input, and then from the output determining the effect of the particular set of parameters employed. Performing several test runs with identical input but varying parameters would demonstrate trends.

Artificial records (Section 3-3) were employed for the majority of tests, and earthquake records only for a few. The reasons for this are the following. Detection of pP and P means to identify presence and exact arrival time. It is important to verify that the filter output will not register P type pulses which are not
part of the input, or suppress them when they are present, or record their arrival times incorrectly. These qualities of the filter can only be verified if every aspect of the input is known (Artificial Inputs); earthquake records, since they are distorted by noise, do not fulfill the latter requirement.

3-3 Filter Inputs as Employed for Testing

Three types of inputs were used:

(i) EARTHQUAKE RECORDS

Three component seismograms digitally stored on magnetic tape were bandpass prefiltered against background noise, and properly rotated as to convert them into the two component REMODE inputs. The procedure for prefiltering and rotation was the same as described by Basham (1967).

(ii) ARTIFICIAL EVENTS WITHOUT NOISE

Up to three sinusoidal segments of different periodicities, starting points, and lengths, would be added to generate either input trace R,Z (Figure 5). Varying degrees in rectilinearity of polarization could be chosen individually for each sinusoidal segment by adjusting the phase difference between its R and Z components.
Figure 5. An example of an artificial filter input consisting of three sinusoidal segments.
The symbols printed on the labels that go with the computer-plotted inputs are explained in the following table. The label's first, second, and third lines of numerical values each describe one of the three sinusoidal segments (Figure 5). Total length of each R,Z is 1,000 data points.

(iii) ARTIFICIAL EVENTS WITH BACKGROUND NOISE

Seismic noise as plotted on traces labeled NOISR and NOISZ was added to the R and Z sums of the sinusoidal segments. In order to be as realistic as possible, background noise from quakeless periods on seismograms was chosen instead of random noise.

<table>
<thead>
<tr>
<th>SYMBOL</th>
<th>MEANING</th>
</tr>
</thead>
<tbody>
<tr>
<td>NUMAQK</td>
<td>IDENTIFICATION NUMBER OF RECORD</td>
</tr>
<tr>
<td>NT</td>
<td>PERIOD OF SINUSOID (DATA POINTS)</td>
</tr>
<tr>
<td>AR (AZ)</td>
<td>AMPLITUDE OF R (Z) SEGMENT</td>
</tr>
<tr>
<td>JSTTR (JSTTZ)</td>
<td>START POINT OF R (Z) SGMT</td>
</tr>
<tr>
<td>JSTPR (JSTPZ)</td>
<td>END POINT OF R (Z) SGMT</td>
</tr>
<tr>
<td>FIDEG</td>
<td>PHASE DIFFERENCE (DEGREES) BETWEEN THE SEGMENT'S R , Z</td>
</tr>
</tbody>
</table>
CHAPTER IV

RESULTS OF TESTS WITH REMODE PARAMETERS

4-1 Directional Properties: INTANG

INTANG (=ANGINC) designates the "specified" direction as explained in Section 2-6. Any P-type pulse arriving at an apparent angle of incidence BETA is attenuated by a factor (see p20)

\[(10a) \quad \cos^M( | BETA - INTANG | )\]

Variation of INTANG when filtering an earthquake (Figure 6) affected the outputs as recorded in Figures 7 through 11. The drastic reduction of the input to essentially three spikes A, B, C is due to the number of convolutions NC=3 which narrows the "phase window" (p17) to \(\cos^{16}( f_R - f_Z )\).

<table>
<thead>
<tr>
<th>FIGURE</th>
<th>INTANG</th>
<th>M</th>
<th>NC</th>
<th>IFTAP</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>15°</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>40°</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>45°</td>
<td>6</td>
<td>3</td>
<td>0</td>
</tr>
<tr>
<td>10</td>
<td>50°</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>75°</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
The absolute magnitudes of the spikes for different INTANGs shall not be compared to each other since the plotting required individual scaling (to 38mm maximum amplitude on each trace).

The maxima of each A, B, C relative to the other two spikes occur at different values of INTANG, as is listed in the following table. Based on the implication of (10a), the apparent angles of incidence for A, B, C can be estimated.

<table>
<thead>
<tr>
<th>SPIKE</th>
<th>INTANG for which the relative maximum occurs</th>
<th>Estimated BETA</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>15°</td>
<td>Below 40°</td>
</tr>
<tr>
<td>B</td>
<td>50°</td>
<td>Between 45° and 75°</td>
</tr>
<tr>
<td>C</td>
<td>75°</td>
<td>Above 50°</td>
</tr>
</tbody>
</table>

This placing of the BETAs belonging to the spikes A, B, C had to be crude because of wide spacing of the INTANG values tried. BETA could be determined more accurately if we would cover the range from 0° to 90° more closely with discrete values of INTANG, e.g. 0, ..., n \( \Delta \alpha \), ..., 90°.

If then the relative maximum (compared to the other spikes)
Figure 6. Filter input for the outputs shown in Figures 7 through 11.
Figure 7. Specified angle of incidence: output for INTRAC=15°.

A

B

C

FR

5 sec → t

A

B

C

FZ
Figure 8. Specified angle of incidence: output for INTANG=40°.
Figure 9. Specified angle of incidence: output for INTANG=45°.
Figure 10. Specified angle of incidence: output for INTANG=50°.
Figure 11. Specified angle of incidence: output for INTANG=75°.
of a particular pulse were found on the output for \( \text{INTANG} = n \Delta \alpha \), then its apparent angle of incidence could be assigned within

\[
(n-1)\Delta \alpha \leq \text{BETA} \leq (n+1)\Delta \alpha
\]

This technique might also be applied to determine the azimuths of such individual spikes. The two components used for input would then have to be in that plane through the ray which is perpendicular to the one employed so far.

If a \( \text{BETA} \) thus determined differs very much from \( 45^\circ \) this is strong evidence that such pulse constitutes scattered energy (SGN). Further clarification of whether or not such a spike would represent one of the basic seismic phases can be obtained from travel time tables if the focal depth of the event is known.

4-2 Directional Properties : M

Variation of the cosine power \( M \) (Section 2-6) when filtering an earthquake (Figure 12) affected the outputs as recorded in Figures 13 through 16.

<table>
<thead>
<tr>
<th>FIGURE</th>
<th>M</th>
<th>INTANG</th>
<th>NC</th>
<th>LW</th>
<th>LAGS</th>
<th>IFTAP</th>
</tr>
</thead>
<tbody>
<tr>
<td>13</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>14</td>
<td>3</td>
<td>45°</td>
<td>0</td>
<td>20</td>
<td>10</td>
<td>0</td>
</tr>
<tr>
<td>15</td>
<td>0</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>16</td>
<td>3</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>
Figure 12. Filter input for the outputs shown in Figures 13 through 16.
Figure 13. Directional discrimination: output for $M=0$, and no convolution.
Figure 14. Directional discrimination: output for \( M=3 \), and no convolution.
Figure 15. Directional discrimination: output for M=0, and 3 convolutions.
Figure 16. Directional discrimination: output for M=3, and 3 convolutions.
For either NC=0 or NC=3, the outputs produced with M=0 or M=3 are practically identical. This may be explained as follows. Inspection of those pulses that are passed by the filter reveals that for a majority the R amplitudes approximately equal the Z amplitudes; i.e. these pulses' apparent incident angles $\beta \approx 45^\circ$. Together with the specified INTANG=45°, the directional factor (10a) then assumes the following values:

<table>
<thead>
<tr>
<th>M</th>
<th>DIRECTIONAL FACTOR</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>$\cos^0(\mid \text{INTANG} - \beta \mid) = 1$</td>
</tr>
<tr>
<td>3</td>
<td>$\cos^3(\mid \text{INTANG} - \beta \mid) \approx 1$</td>
</tr>
</tbody>
</table>

Such minor differences for M=0 or M=3 explain the quasi-identity of records with either value M.

The relative lack of directional discrimination, even for M=3, against pulses arriving at an apparent angle of very close to 45°, can be quantitatively verified in Figure 17 (Adapted from Griffin, 1966b). Greater directional sensitivity can be achieved through large M. However, this may have disadvantages which were pointed out on p21.
Figure 17. Schematic representation of $\cos^M(|\text{INTANG - BETA}|)$ (after Griffin, 1966a).
Reasons for tapering the truncated filter operator, as well as the function of the parameter IFTAP, were explained in Section 3-1.

Different types of tapering (also no tapering), with a non-convolved as well as a twice-convolved filter, were tried on an artificial record that consisted of three sinusoidal segments of different periodicities superimposed on seismic noise (Figure 18). Some results are presented in Figures 19 through 24.

<table>
<thead>
<tr>
<th>FIGURE</th>
<th>IFTAP</th>
<th>TYPE OF TAPERING</th>
<th>CONVOLUTIONS</th>
</tr>
</thead>
<tbody>
<tr>
<td>19</td>
<td>0</td>
<td>NO TAPERING</td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>2</td>
<td>HAMMING</td>
<td>0</td>
</tr>
<tr>
<td>21</td>
<td>4</td>
<td>DANIELL</td>
<td></td>
</tr>
<tr>
<td>22</td>
<td>0</td>
<td>NO TAPERING</td>
<td></td>
</tr>
<tr>
<td>23</td>
<td>2</td>
<td>HAMMING</td>
<td>2</td>
</tr>
<tr>
<td>24</td>
<td>4</td>
<td>DANIELL</td>
<td></td>
</tr>
</tbody>
</table>

Within each of the two series (NC=10, NC=12) the three output records processed with different types of tapering are, if not exactly then for all practical purposes, identical. In further tests it was established that this holds true also for two other types of tapering
Figure 18. Filter input for the outputs shown in Figures 19 through 24.
Figure 19. Effect of tapering: output for NO TAPERING, and no convolution.
Figure 20. Effect of tapering: output for HAMMING window, and no convolution.
Figure 21. Effect of tapering: output for DANIELLL window, and no convolution.
Figure 22. Effect of tapering: output for NO TAPERING, and 2 convolutions.
Figure 23. Effect of tapering: output for HAMMING window, and 2 convolutions.
Figure 24. Effect of tapering: output for DANIELL window, and 2 convolutions.
(IFTAP=1 and IFTAP=3; see p24), and for higher order filters (i.e. a larger number of convolutions).

4-4 Normalization: Summation Limits

\[(X_{\text{NORM}}(t))^2\] are proportional to the reciprocals of averaged signal energy (Formula 5, pl4):

\[
(5) \quad (X_{\text{NORM}}(t))^2 = 1 \sqrt{\sum R^2(t) \cdot \sum Z^2(t)}
\]

For simple harmonic (sinusoidal) oscillations, the \(X_{\text{NORM}}(t)\) are proportional to the reciprocals of averaged signal amplitude; for non-harmonic seismic motion this will still be approximately true.

Such averaged amplitude should represent as closely as possible the signal amplitude at point \(t\); for this reason, the sums are taken over a time window including \(t\). Tried were three window types to which we assign the following symbols:

<table>
<thead>
<tr>
<th>WINDOW</th>
<th>SYMBOL</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\sum_{t-LW/2}^{t+LW/2})</td>
<td></td>
</tr>
</tbody>
</table>
Through trial runs we found that for several earthquakes tested it did not matter whether \( \sum \), \( \sum \), or \( \sum \) was employed.

If, however, earthquakes with sharp onsets on a very low noise level (per se, or after prefiltering) are to be processed, the \( \sum \) type is to be preferred. This is suggested by the following considerations (Figure 25). Theoretically, we can predict the effect of \( \sum \), \( \sum \), or \( \sum \) on such input; this is illustrated in Figure 25, and was confirmed by experiments with artificial inputs.

(i) \( \sum \): XNORM will be extremely large when the filter operator reaches A, because the left oriented window samples only very small amplitudes into the denominator's sum (5) while to the left of A; this causes the spike A'. Once to the right of A, larger values are sampled, thus preventing further spikes like A'.

(ii) \( \sum \): The right-oriented half of the centered window prevents case (i) at A, and the left-oriented half prevents case (iii) at B.

(iii) \( \sum \): The counterpart to (i), with spike B'
Figure 25. Schematic representation of the effects of different types of normalization applied to an input with extremely low noise level.
from B because of the right-oriented window then covering the very-small amplitude segment to the right of B.

On a first look, it is tempting to try \( \sum \) for an onset detector. However, as we understand from the previous explanations, the left-oriented spike \( A' \) will only occur when firstly the background noise is of extremely small amplitudes, and secondly the onset \( A \) is sharp. When these two conditions are fulfilled, an onset detector is unnecessary.

In order then to avoid seemingly erratic filter responses of types (i) or (iii), we recommend to always use \( \sum \).

4-5 Time Window and Number of Lags: \( LW \) and \( LAGS (=T_{max}) \)

From Griffin's comment (p22) on the most effective length \( LW \) of the time window we understand that this strongly depends on the particular signal-noise characteristics of a record. Consequently, we feel that trial and error, rather than a theoretical calculation, may be the best way to optimize \( LW \) for any particular application.

For \( LAGS \), Griffin (1966a) recommends that it should not be much larger than \( LW/2 \) in order to retain within the cross-correlation significant portions of both the \( R \) and \( Z \) segments centered on \( t \).
An earthquake record (Figure 26) was subjected to filtering with differing LW and LAGS as listed in the following table.

<table>
<thead>
<tr>
<th>FIGURE</th>
<th>LW</th>
<th>LAGS</th>
<th>NC</th>
<th>IFTAP</th>
</tr>
</thead>
<tbody>
<tr>
<td>27</td>
<td>40</td>
<td>24</td>
<td></td>
<td></td>
</tr>
<tr>
<td>28</td>
<td>20</td>
<td>10</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>29</td>
<td>4</td>
<td>4</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

LW=40 (Figure 27) confirms Griffin's point that the length of the time window should be such that it is of the same length as the signal period. The dominant signal period is 1cm, and LW=40 corresponds to slightly less than 1cm (1cm = 46.3 points). This output shows the onset of the quake very conspicuously and also enhances other rectilinear motion that is less well discernible on the input.

LW=20. This record, even though it retains most of the pulses which were conspicuous on the preceding one, it does not enhance but rather minimize the onset. An explanation may be that the shorter window could not sample enough rectilinear P motion to the right of the onset point; consequently, at this point the even part of the cross-correlation c(T) failed to be large, resulting in the output's small onset.
Figure 26. Filter input for the outputs shown in Figures 27 through 29.
Figure 27. Effect of varying window width $W$ and maximum $24$.

[Graph showing waveforms with labeled axes and time markers]
Figure 28. Effect of varying window width LW and maximum lag: output for LW=20, and LAGS=10.
Figure 29. Effect of varying window width LW and maximum lag: output for LW=4, and LAGS=4.
LW=4, LAGS=4 (Figure 29) makes the outputs FR,FZ look rather uncorrelated, even though some of the larger peaks show on both traces simultaneously. This suggests that the filter response is random and dominated by noise, thus again supporting Griffin's argument that LW should be long enough to cover a full signal period.

4-6 Number of Convolutions: NC

The sensitivity of the "phase window", i.e. the power to discriminate against motion which is not strictly rectilinear (Section 2-5), is determined by the number of convolutions of the filter operator with itself:

\[ \text{FILTER RESPONSE } \propto \cos^2(NC+1) \]

An increase of NC by only one unit may make the filter very much sharper, as is illustrated in this table:

<table>
<thead>
<tr>
<th>NUMBER OF CONVOLUTIONS</th>
<th>PHASE WINDOW</th>
</tr>
</thead>
<tbody>
<tr>
<td>NC</td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>[ \cos(\mathcal{L}_R(\omega) - \mathcal{L}_Z(\omega)) ]</td>
</tr>
<tr>
<td>1</td>
<td>[ \cos^4( ) ]</td>
</tr>
<tr>
<td>2</td>
<td>[ \cos^9( ) ]</td>
</tr>
<tr>
<td>3</td>
<td>[ \cos^{16}( ) ]</td>
</tr>
</tbody>
</table>

NC=3 seems to be the maximum number of convolutions to produce outputs that are realistic in terms of
pulses passed or rejected when the filter is used as a P wave detector. This was established in tests. Griffin (1966a) states: "As the number of convolutions is increased to two and three, ..., and signal waveform (becomes) more erratic. The overall effect in this case is ... a loss in signal coherence between stations." One reason is that many P pulses which we wish to register on the output will, as they reach the station, be slightly non-rectilinear due to contamination by S-wave-converted phases. Such P motion would easily, and unwantedly, be rejected if we kept the phase window too narrow by using too large an NC.

An example of how the power of discrimination against non-rectilinear motion increases with NC is shown in Figures 31 and 32. The input (Figure 30) consisted of three sinusoidal segments of different periodicities, with 45 degrees phase difference between each segment's R and Z components. The FZ output traces for different NCs are presented as follows:

<table>
<thead>
<tr>
<th>FIGURE</th>
<th>NC</th>
<th>LW</th>
<th>LAGS</th>
<th>INTANG</th>
</tr>
</thead>
<tbody>
<tr>
<td>31a</td>
<td>0</td>
<td>20</td>
<td>10</td>
<td>45°</td>
</tr>
<tr>
<td>31b</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>32a</td>
<td>2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>32b</td>
<td>3</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Figure 30. Filter input for the outputs shown in Figures 31 and 32.
Output FZ for NC=0 (31a). Output FZ for NC=1 (31b).

Figure 31. Effect of varying the number of convolutions.

Figure 32. Effect of varying the number of convolutions.
The leftmost sinusoidal segment with a period of NT = 200 points is not affected by the filter, no matter how large NC. The reason is that here the time window is too short compared to the period (LW/NT = 1/10). Such short a window cannot sample enough of the oscillation as to establish the odd or even function characteristics of the corresponding cross-correlation operator which is the basis of REMODE filtering.

For the two segments with periods comparable to or shorter than LW (NT=50, NT=5), the filter works. The expected effect of successively stronger suppression with successively larger NCs is verified.
CHAPTER V

SUMMARY AND CONCLUSIONS

5-1 Summary

In testruns, two-component digital records were filtered with the "REMODE 5A" polarization filter (Griffin, 1966a and 1966b). The inputs were either earthquakes (three-component seismograms reduced to two by rotating the coordinate system), or artificial sinusoidal wave-trains with equal amplitudes on both traces. Artificial records with and without background noise were used. The time domain REMODE filters pass or enhance seismic motion only if the polarization is more rectilinear than random and elliptical. They are time varying which makes them expensive in computer time. REMODE 5A is the most sharply discriminating, most complicated, and computationally most expensive type within the REMODE class. Previously, other workers had successfully applied simpler REMODE filters to seismograms (e.g. Griffin, 1966a and 1966b; Basham, 1967 and 1969). The aim of this study was to investigate whether REMODE 5A would have much advantage over the sim-
pler types, and to determine optimal values for the filter parameters.

These questions were seen against the background of nuclear test detection. One point of distinction between earthquakes and explosions is that the latter take place at much shallower depths than most quakes. Focal depth can be determined from a seismogram if both the P and pP phases are clearly distinguishable. On real seismograms these phases (especially pP) are often covered by background noise and signal-generated noise (SGN). REMODE 5A can suppress much noise provided that the polarization of the latter is different from that of the (rectilinear) P phases. SGN, generated by multiple refractions and reflections in the crust's layers and inhomogeneities, is not suppressed with such certainty since it may be rather rectilinear.

REMODE 5A, through its self-convolution providing for stronger discrimination against motion which is not purely rectilinear, was found to be better at enhancing rectilinear phases from strongly noise-contaminated records than the non-convolved types. However, if the sensitivity was strongly increased by raising the number of convolutions above \( NC=2 \), much rectilinear motion would be deleted as well, and those output spikes which indicate rectilinear phases would become quite erratic.
Similarly, signal may be lost if the power \( M \) governing directional discrimination is chosen too large. The reason is that because of the complexity of the earth we cannot exactly specify the incident angle of the \( P, pP \) rays.

The apparent incident angles of individual spikes can be roughly determined if the range of 0 to 90 degrees is scanned with the specified angle of incidence (INTANG) by processing the record several times.

The length \( LW \) of the time window within which the cross-correlation between the two input traces is taken must not be small compared to the period of a sought-for rectilinear phase in order that the latter be registered. Especially, \( LW \) has to be large enough in order to enhance onsets. The optimum \( LW \) is best determined by trial and error.

The character of the output was not significantly affected by tapering the truncated filter operator. We therefore recommend that tapering be deleted.

Even though REMODE 5A proves successful in removing background noise and much of the SGN, it does not solve the problem of picking \( pP \) from an extended \( P \) coda. For very shallow events, \( pP \) follows so shortly after the \( P \) onset that \( pP \) may be hidden in the extended \( P \) wavetrain,
and since \( pP \) is an echo of \( P \), the two phases are of the same (rectilinear) polarization.

5-2 Conclusions

REMODE 5A has potentially unlimited sensitivity in terms of discrimination against motion which is not of exactly linear and longitudinal polarization, and which does not arrive from a specified direction.

However, applying the full power of REMODE 5A leads to disappointment. Too high a sensitivity can cause the loss of \( pP \) or \( P \). Thus, in practical applications one should use the filter with parameters that render it less sensitive (e.g. \( NC=1 \), \( M=6 \)). Comparing the outputs produced by such REMODE 5A with those from the considerably simpler REMODE 3A (Basham, 1967), the 5A outputs look clearer because of a more rigid suppression of small-amplitude oscillations which on the 3A outputs are still present between the large (and only significant) spikes. However, 5A would not detect rectilinear motion ignored by 3A. Taking into account also that 5A requires more computer time than 3A we would not, for the routine processing of seismic records, prefer REMODE 5A over 3A.

It then appears to the author that REMODE filters of the here investigated form will not attack the problem of nuclear test detection more successfully than shown by Griffin and Basham.
REFERENCES


Griffin, J. N., Application and development of polarization (REMODE) filters, Seismic Data Laboratory Report No. 141, Earth Sciences Division, Teledyne, Inc., April, 1966a.