Geophysica (1992), 28, 1-2, 29-40

Polarization Detector: A New Approach Without Eigenvalue Problem Solution

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(Received: January 1993; Accepted: April 1993)

Abstract

A new approach to polarization detecting is presented. The detector takes into account as well the incoming energy as the changes of polarization state.

A polarization filter is used to amplify the linearly polarized signals of P-phase before detecting local and regional events. The filtering is based on computing predicted coherency as a measure for linear polarization for each sample and defining gain factor using it.

The detector itself tries to find rapid changes in polarization state. The type of polarization is not studied, only its changes. This is done without solving the eigenvalue problem of the covariance matrix, but only the cross-powers between vertical and horizontal components are examined. This kind of approach is much more efficient than the earlier polarization detectors, especially from the point of view of computing speed.

The detector is tested with teleseismic and regional events. The results show that the new kind of polarization detector easily finds the events, detected and reported by FINESA array and FINET network. The false alarm rate is found to be around 5 % for regional and local events.

The polarization method and F-test were applied to automatic phase picking.

1. *Introduction*

Most of the detectors in seismology are based on STA/LTA-type algorithms, which compare signal power or related quantities in two windows. In the Finnish seismic network *FINET*, shown in Figure 1 and described in detail by *Teikari* and *Suvilinna* (1991), the detector developed by *Murdock* and *Hutt* (1983) and *Murdock* and *Halbert* (1987) is used and the system responses of the instruments used in this study are shown in Figure 2. The Murdock-Hutt detector monitors peak-to-trough values of incoming data. When levels of three or four consecutive values exceed some preset thresholds, an event is detected. For the recordings of the *FINESA* small aperture array a pure *STA/LTA*-detector is used. Teleseismic events have the main signal contribution on the vertical component owing to nearly vertical incidence angles. When we are dealing with local or regional events that produce horizontal amplitudes equal or larger than vertical components, a significant part of event energy is ignored. Also the polarization effect is left unused.

Published by the Finnish Geophysical Society, Helsinki

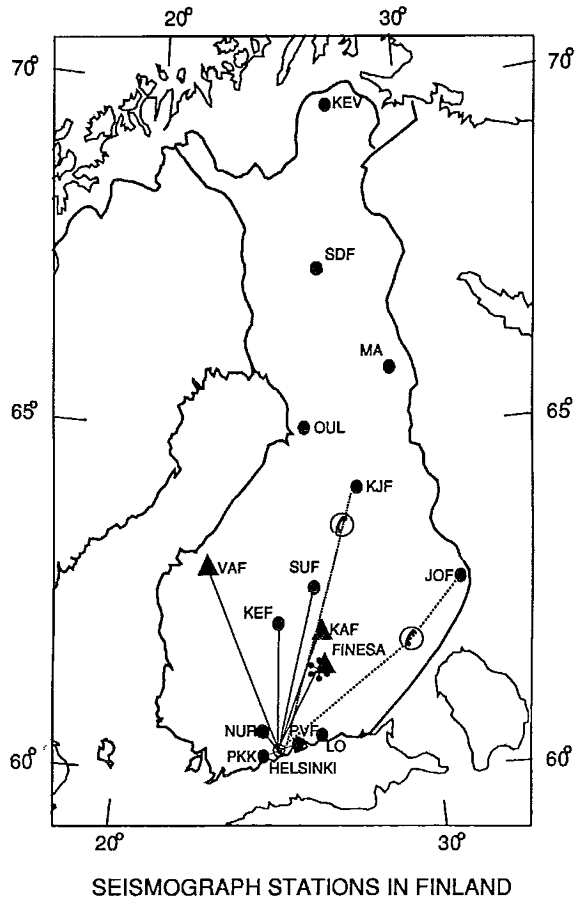

Fig. 1. Seismic stations in Finland in 1992 according to Teikari and Suvilinna (1992). The constant lines present stations with on-line recording at the national data center in Helsinki, the dotted lines dial-up stations. The triangles show stations, which have three-component registration and were used in this study.

During the last ten years data-adaptive methods were developed widely for detecting weak seismic events at any distances (*Ferber* and *Harjes* 1985, *Kushnir et al.* 1990, *Tarvainen* 1991, *Savin et al.* 1992). Those efforts produce moderate detection accuracy and efficiency, but if the preset detection threshold is too low, they can produce a great amount of false alarms. *Joswig* (1990) used noise adaptive suppression and pattern recognition for signal detection. That method produces very few false alarms, since it is based on recognizing wanted events according to previous reference events. *Ruud* and *Husebye* (1992) introduced a detector for three-component data, which can also produce daily single station bulletins.

In our polarization detector only the amount of changes of polarization is studied, not the type of polarization. The former polarization detectors applied the eigenvalue problem solution. Our aim was to develop a new kind of polarization detector, where no such solution would be needed.

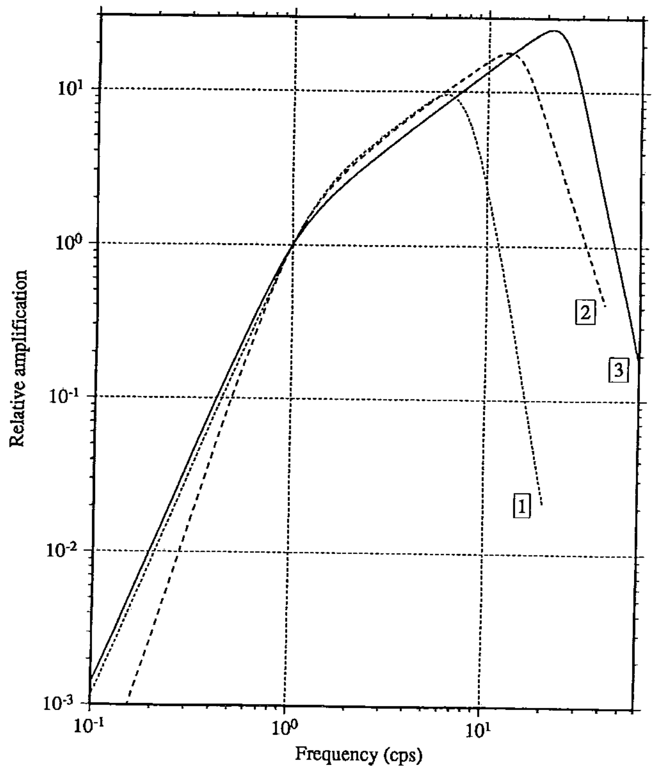

Fig. 2. The response curves of the instruments used in this study normalized into the constant displacement at 1 Hz. The numbers denote 1=KAF, 2=FIA1 and 3=VAF respectively.

2. *Theoretical background for polarization detector*

The noise is assumed to be isotropic and its coherency between different Cartesian channels is expected to be zero. Registration is assumed to be a sum of the noise (N) and the signal (S)

$$y(t) = S(t) + N(t) \tag{1}$$

The conventional approaches of polarization filtering were based on the formation of covariance matrix (*Montalbetti* and *Kanasewich* 1970). The covariance matrix in a three-dimensional Cartesian coordinate system can be determined as

$$C=\begin{bmatrix}\langle Z(t)Z^{*}(t)\rangle & \langle Z(t)N^{*}(t)\rangle & \langle Z(t)E^{*}(t)\rangle \\ \vdots & \ddots & \vdots \\ \langle E(t)Z^{*}(t)\rangle & \cdots & \langle E(t)E^{*}(t)\rangle\end{bmatrix} \tag{2}$$

where the matrix elements present the cross-powers of recorded components. When matrices from consecutive time windows have been formed, their eigenvectors and eigenvalues are computed to determine the polarization state as a function of time (*Vidale* 1986). We take only the cross powers of the vertical component with horizontal components, actually the two entities of the uppermost row, $<Z(t)N^{*}(t)>$ and $<Z(t)E^{*}(t)>$. We computed the cross-powers within sliding windows of 5 seconds, using a time step of 1 sample. Accordingly we received two time series, which have the same sampling rate as the original data.

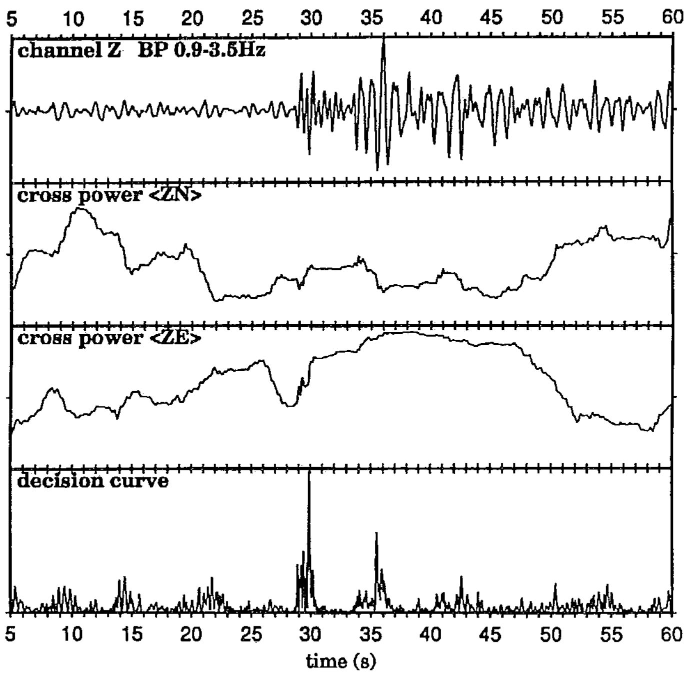

Fig. 3. The forming of the decision curve. In (a) the vertical component of KAF recording is shown. The event is a small seismic event in Lousiana USA in December 1992 and the distance is 76°. In (b) and (c) the vertical-horizontal cross correlograms are expressed and in (d) the summed differences of crosscorrelograms divided by the LTA of 300 seconds are shown. These differences get high values at the onsets of the phases.

Then we study drastic changes in the cross-powers. Maximum differences in $<Z(t)N^{*}(t)>$ and $<Z(t)E^{*}(t)>$ within a 0.2 second long sliding window are summed to define a dynamic difference curve with the same sampling rate as the original time series. When this difference (derivative) curve is divided by an *LTA* of 300 seconds, we get the final decision curve. The forming of this decision curve is shown in Figure 3. If the value of decision curve exceeds some preset threshold, an event is detected. The flow chart of the detector is shown in Figure 4.

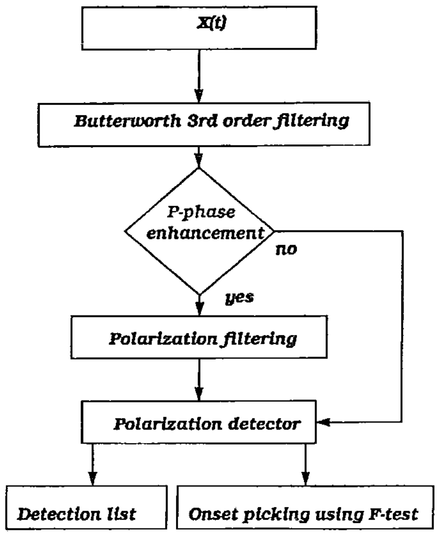

Fig. 4. The flow chart of the polarization detector

2.1 *Polarization filtering*

To enhance P-phase onsets we used simple polarization filtering based on the predicted coherency. The predicted coherency was computed to measure the amount of linear polarization ahead of each sample. Further the amount of linear polarization was applied as a gain factor of polarization filter. The predicted coherency according to *Roberts et al.* (1989) can be expressed by

$$C = 1 - \frac{\left\langle \left(y_z - Ay_n - By_e\right)^2 \right\rangle}{\left\langle y_z y_z \right\rangle} \tag{3}$$

where

$$A = -R\cos(az) \tag{4}$$

$$B = -R\sin(az) \tag{5}$$

az is the backazimuth, which can be expressed by

$$az = \arg\tan\left(\frac{-\langle y_e y_z \rangle}{-\langle y_n y_z \rangle}\right). \tag{6}$$

Further R estimates the ratio between the displacements of the vertical to radial components, being

$$R = \frac{\langle y_z y_z \rangle}{\sqrt{\left(\langle y_n y_z \rangle^2 + \langle y_e y_z \rangle^2\right)}}. \tag{7}$$

The recorded time series $y(t)$ is assumed to be a mixture of linearly polarized signal (S) and noise (N_o), which includes everything else, also non-linearly polarized parts of the signal. Using equations (4), (5) and (7) the signal can be expressed as

$$S(t) = R(-\cos((az)y_n(t) - \sin(az)y_e(t))) = Ay_n(t) + By_e(t) \tag{8}$$

Consequently the recorded signal gets the form

$$y(t) = A\,y_n(t) + By_e(t) + N_o(t)\,. \tag{9}$$

When we solve noise in equation (9) we get the expression inside the brackets in the equation (3). In other words, if the signal is completely linearly polarized, the predicted coherency reaches its maximum value 1. This kind of filtering is especially beneficial with local events. With the help of polarization filter we can detect P-phases of weak local events instead of more dominant Lg-phase.

3. *Data and results*

3.1. *Testing the polarization detector with local and regional data*

The polarization detector was tested with local, regional and teleseismic events. For local and regional events the detection logs of *FINESA* 3-component substation *FIA1* (coordinates 61.4°N, 26.1°E) were compared with *FINESA* automatic location lists. The

FIA1 substation is located on the ring 1, not at the center of the array as in the case of *NORESS, ARCESS* arrays in Norway. Test period covered 9 days (18. - 23., 25., 28. and 30 July 1992) in summer 1992. In polarization detector a high-pass filter was used with cut-off frequency at 2 Hz. Further polarization filter was applied to the data. The polarization detector was tuned to detect most of the events in *FINESA* automatic bulletin and to keep the total number of detections per day relatively low. Consequently during the test period 486 detections were found, which meant approximately 50 detections/day.

FINESA automatic bulletins included 105 local and regional events during the same period. The polarization detector found 76 of these events. The detections consisted of 50 first P-phase detections, 21 Lg-phase detections and 5 detections of other phases respectively. Other detections, which were not included in *FINESA* bulletins were mostly small local and regional events of magnitude less than 1.0 and weak teleseismic events. The false alarm rate was close to 5 %. The events of July 28, 1992, found by the polarization detector and the STA/LTA-detector at *FINESA* are shown in Table 1. The events of the *FINESA* automatic bulletin, that were not detected were small ones $M_L \leq 1.2$ or from regional distances beyond 400 km. The sensitivity is relative to the distance and the size of the event. The polarization detector did not miss any clear event. In Figure 5 a quarry blast in Russian Karelia, recorded at *FIA1* substation of *FINESA,* is presented. The magnitude of the event is M_L=2.3 and the P-phase is emergent. Using a band-pass filter with the cut-off frequencies at 3 Hz and 10 Hz the onset of P-phase became clearer, but after polarization filtering the P-phase became very prominent. The decision curve formed

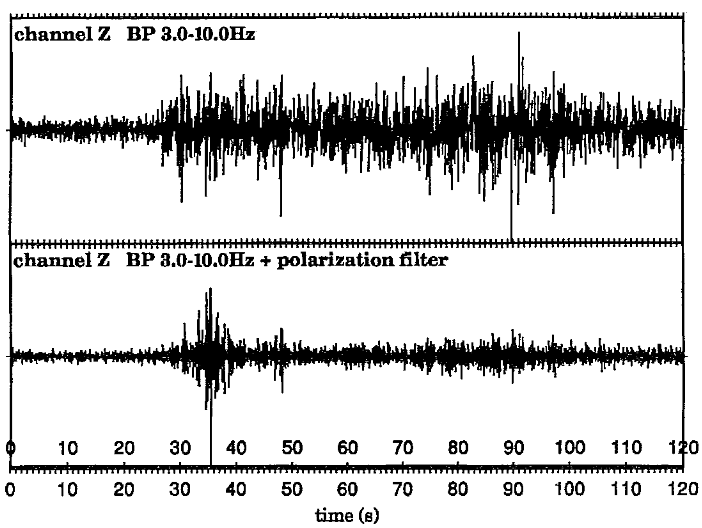

Fig. 5. A mining explosion in Russian Karelia, 64.3°N, 30.3°E on December 13 1992 at 09:59:16 GMT. The distance from VAF was approximately 400 kilometers. When only band-pass filtering was used, the signal did not become significally clear. When the polarization filter was applied to the recording, the first P-phase became very distinct.

from summed differences of cross powers showed clearly the event. The onsets of the different phases were studied by using the *F*-test (*Abramowitz* and *Stegun* 1970). The *F*-test is the ratio of variances of two separate populations. In our study two groups for *F*-test were formed from the rectified samples of two successive data windows. In Figure 6 there are shown the results of the *F*-test phase picking of an event in Estonia.

Table 1. Comparison of detections of the *FINESA* array and the polarization detector. Detection times of first detected P-phase, distance, latitude, longitude and M_L-magnitude according to *FINESA* daily automatic bulletin. The rest 2 columns present the first detected phase by polarization detector and the detection time difference of these two different detection systems. The date was 28 July 1992. The asterisks refere to later phase detection.

FINESA STA/LTA detector					Polarization detector	
Detection phase and time	Latitude	Longitude	Distance (km)	Magnitude	Detection phase and time	δT
Pn 07:43:01.1	59.3	27.8	256.7	1.1	Pn 07:43:01.8	0.7
Pn 08:12:44.0	60.2	29.5	232.0	2.1	Pn 08:12:43.6	-0.4
Pn 08:30:47.8	60.9	29.8	206.4	1.0	Pn 08:30:48.0	0.2
Pn 08:32:44.7	60.2	25.4	139.3	1.3	Pn 08:32:45.0	0.3
Pn 09:01:49.5	59.4	27.7	247.8	1.1	Lg 09:02:11.1*	-
Pn 09:08:38.7	59.5	27.2	229.5	1.5	Pn 09:08:39.2	0.5
Pn 09:16:59.1	60.1	23.0	221.9	1.3	Lg 09:17:25.9*	-
Pn 09:18:56.3	60.1	25.4	158.4	0.8	-	-
Pn 10:21:49.3	60.6	29.2	192.3	1.6	Pn 10:21:50.2	0.9
Pn 10:36:53.6	61.6	29.3	173.9	0.5	-	-
Pn 10:38:53.8	60.9	30.0	221.1	1.0	Pn 10:38:54.7	0.9
Pn 10:59:41.9	63.0	27.5	186.9	1.5	Pn 10:59:42.7	0.8
Pn 11:34:46.6	59.3	26.7	240.9	2.3	Pn 11:34:46.9	0.3
Pn 11:40:59.4	62.7	23.4	199.5	1.7	Pn 11:41:00.6	1.2
Pn 12:22:17.6	50.1	17.4	1364.1	2.7	-	-
Pn12:37:51.3	59.3	27.2	245.9	1.5	Pn 12:37:51.8	0.5
Pn 14:05:40.1	59.6	25.3	211.7	1.3	Pn 14:05:40.3	0.2
Pn 14:32:44.2	60.2	25.2	150.7	1.3	Pn 14:32:45.0	0.8
Pn 14:35:53.2	59.5	25.2	223.9	1.6	Pn 14:35:54.3	1.1
Pn 14:48:31.2	63.5	26.0	232.2	0.8	-	-
Pn 15:08:03.5	58.0	22.3	436.4	1.2	-	-
Pn 19:48:10.5	55.6	17.4	824.7	1.7	-	-

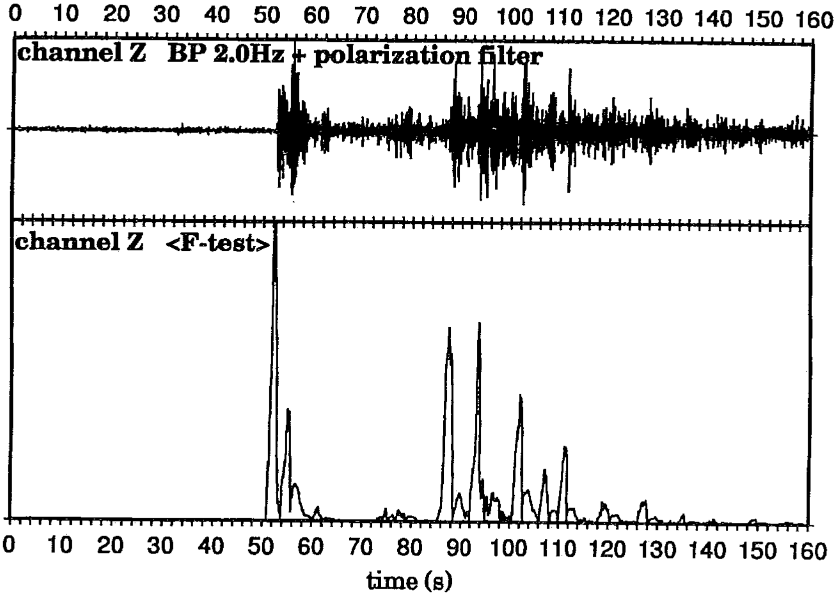

Fig. 6. A quarry blast in Estonia showing the results of F-test phase picking. In (a) the band-pass and polarization filtered signal is shown and in (b) the F-test analyzed phase onsets of some crustal phases are shown.

4. *Testing the polarization detector with teleseismic data*

The teleseismic signals have nearly vertical incidence angles and are correspondingly weak in the horizontally oriented components.

The current detector system at the *FINET* uses *Murdock* and *Halbert* (1987) application from the original *Murdock* and *Hutt* (1983) detector with 7 filtering bands and a voting system. These filtering bands are listed in Table 2. The system applies two groups of three stations, but only two high-frequency filtering bands are used with three stations in southern Finland. If a detection occurs at three stations within an acceptable time window, the detection is assumed to be a potential event. For teleseismic events the length of the time window of the voting system was determined by using the lowest possible apparent surface velocities for teleseismic P-waves. The adjustment of the detection thresholds is very essential for peak-to-trough detectors to ensure a reasonable false alarm rate.

Table 2. The cut-off frequencies of the 3rd order Butterworth filters used with the Murdock-Hutt detection system in *FINET* network.

Type of Filter	Low-frequency cutt-off	High-frequency cut-off
1) Butterworth 3rd order	0.500	0.9555
2) Butterworth 3rd order	0.6912	1.3208
3) Butterworth 3rd order	0.9555	1.8258
4) Butterworth 3rd order	1.3208	2.5240
5) Butterworth 3rd order	1.8258	3.4890
6) Butterworth 3rd order	2.5240	4.8239
7) Butterworth 3rd order	3.4890	6.6667

The teleseismic events were detected using two three-component stations of *FINET* (*VAF* ; 63.0°N, 22.7°E and *KAF*; 62.1°N, 26.3°E). At first a Hutt-Murdock detector was used with one pre-filtering band from 0.9 to 3.5 Hz. Threshold was the same as in the routine detector system of the whole network. A detection was accepted if both of the stations detected it within a fixed time window. This meant up to 230 detections/day.

The polarization detector was tuned to make about the same amount of daily detections. During the test period of 9 days (18. - 22., 24. - 26. and 28. July 1992) the whole network detected 97 teleseismic events. When data of the stations *VAF* and *KAF* only were used, the Hutt-Murdock detector found 58 of these events, which were 60 % of the detections obtained from the whole network. With polarization detector *VAF* and *KAF* found 81 events, which is 84 % from the events of the whole *FINET*. So the polarization detector found 23 events more than Hutt-Murdock detector for the same configuration. This test was made to compare the detectors on certain threshold levels, using 2 stations, not to build a new detector system for the whole network. So, large false alarm amount was accepted. If more stations are included in the detection process, the false alarm rate will drop. When the routine detector system was developed, it was found that the number of false alarms dropped 75 % by using 3 stations instead of 2 in the voting system.

5. *Polarization detector - computational efficiency*

An important aspect of a detector design is computational efficiency. Otherwise it would not be useful for on-line data analysis. The speed of our polarization detector was studied with 20 Hz data of *KAF* and 100 Hz data of *VAF*. The corresponding CPU time on a SUN SPARC IPC workstation with 24 MB of RAM is shown in Table 3. Twenty-four hours of data from the station KAF can be analyzed in 6 minutes. When a higher sampling rate is used, the computing speed becomes remarkably slower. For 100 Hz data 24 hours took approximately half an hour. Using polarization filtering increases run time vigorously, as shown in Table 3.

Table 3. The CPU times needed to run 1 hour of seismic data with different sampling rates and different filtering configurations.

	CPU times in minutes and seconds	
Type of detector combination	Sampling rate = 20 Hz	Sampling rate = 100 Hz
Polarization detector	0' 15"	1' 20"
Polarization detector+3rd order Butterworth filter	0' 22"	1' 51"
Polarization detector + 3rd order Butterworth + polarization filter based on the predicted coherency	0' 56"	12' 40"

6. *Concluding remarks*

We have herewith introduced a new effective approach to the detection of seismic events. The detector was found to work fast and adequately.

The detector uses energy and polarization state of the arriving signal. The polarization detector gives also as output the azimuth, slowness, ratio between vertical and horizontal components and predicted coherency. So the detector works also as a selector for teleseismic and regional events.

The detector was tested as well with teleseismic as local and regional events and the results show that the new detector finds easily the events detected and reported by other detection systems. The false alarm rate was found to drop to a lower level than in traditional detection systems. The polarization filtering using predicted coherency was found to be an effective method to enhance P-phase onsets of local and regional events. The new detector detected teleseismic events more efficiently, owing to the amplification of the signal by the predicted coherency method. This method also improved the P-phase detections, and only seldom detections occurred in later onsets.

When the detection times of *FINESA* were compared with detection times of polarization detector, in general they differed only some tenths of seconds. Some weak local or regional events were missed by the polarization detector or the first detected phase was Sn or Lg.

The polarization detector does not need as much prefiltering as some traditional detectors. So it is very similar in that sense to the data-adaptive detectors (*Kushnir et al.* 1990, *Tarvainen* 1991, *Savin et al.* 1992). Under noisy conditions or very low S/N cases the polarization filtering significantly improved detectability.

Acknowledgments

The authors thank Professor Eystein S. Husebye for his kind advice and comments of the manuscript to improve the contest and purify the ideas of the work. The work was financially supported by the Finnish Academy Of Sciences And Letters (grants of Vilho, Yrjö and Kalle Väisälä).

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