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# A new approach for three-component seismic array processing

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**Abstract**
The new concept and methodology of regional seismic arrays (RSA) equipped by three-component (3-C) sensors (*Z, NS, EW*), are proposed. Such system could be more perfect tool of Earth interior investigations. This aim can be achieved by introduction of polarization filtering of 3-C seismic vibrations as an effective means of noise suppression and robust detection and identification of secondary body phases of the signals. The proposed algorithm is based on: 1) linear-phase band pass frequency filtering of $N$ 3-C records in $M$ bands; 2) polarization filtering of all 3-C records in all $L$ directions where array beams are routinely oriented; 3) calculation of $L$ beams in $M$ bands using polarized $P$, $SV$ and $SH$-traces of individual sensors; 4) detection of signals on the $L*M$ $P$, $SV$ and $SH$-traces; 5) location of the event. The main new procedures are 2) and 3). Due to these new approaches the procedures 4) and 5) will be improved in comparison with those routinely used today at RSA's. This work includes the theoretical consideration of proposed method efficiency and preliminary experimental results.

**Key words** *earthquake – regional seismic array – polarization filtering – beam – method*

## 1. Introduction

The method of associating seismic vibrations for the purposes of rapid detection and location of weak remote seismic events began to be used in seismology in the 1960s in connection with the problem of monitoring underground nuclear weapon tests. Over the past 30 years, tests have been conducted on seismic arrays with a variety of apertures, configurations and technical characteristics. These arrays were designed to detect signals with epicentral distances in the teleseismic and regional ranges: they range from the giant LASA-type systems in the United States (525 sensors over a 200 × 200 km area) (Green *et al.*, 1965) to modern regional high-frequency mini-arrays, the first of which (NORESS) was set up in Norway in 1984 (25 sensors over an area 3 km across) (Mykkeltveit, 1985).

The Ad Hoc Group of Scientific Experts (GSE) of Conference on Disarmament made a report about the seismological evaluation of the second technical test (GSETT-2). This report based on the analysis of the reporting of 3175 events from stations in the Final Event Bulletin, and it showed that seismic arrays play a crucial role from the viewpoint of seismic event detection and location. If these arrays had not participated in the test, the remaining arrivals would be enough to define only 911 events (CD/1148, 1992; GSE/35/CRP.228, 1993). A major contribution to this result was provided by the arrays of the latest generation, firstly oriented to detect high frequency regional signals of magnitude $m_b$ 2-2.5 and over.

In the light of these results, arrays together with single-site three-component seismic stations have been assigned a major role, which in the global seismic monitoring system has been currently developed in the GSE. It may be also noted that regional seismic arrays are an effective means of monitoring the interior of plates where seismic activity is very low, especially in regions where it is difficult to gain access in order to develop local and regional networks. At the same time, a number of difficulties are involved in the processing of data from such arrays. They are related to the presence of a significant number of spurious detections and identification of secondary phases, primarily of $S$-waves.

The Intelligent Monitoring System (IMS) (Bache *et. al.*, 1990), which has been currently developed in the United States, is based on the joint analysis of data received simultaneously to the processing center from a number of seismic arrays. This system allows to improve the quality of the final events bulletin substantially. This is demonstrated, *inter alia*, by the results which have been currently received (Bratt *et. al.*, 1990; Swanger *et. al.*, 1992). However, there are grounds for supposing that substantial improvement may be made in the processing of data from a single NORESS-type array, using the polarization characteristics of seismic motions picked up by the three-component sensors in such an array.

The present paper reviews a new method of processing seismic information based on the use of the polarization characteristics of the signal and noise received from three-component sensors in a regional seismic array.

## 2. Statement of problem and method

Nowadays the method traditionally used for processing array data is based on the use of recordings from vertical sensors during beam forming, *i.e.* tuning the array to detect signals from the regions of interest. In this procedure the signal-to-noise (S/N) ratio increase is achieved through suppression of those noise components which are outside the pre-detection filter frequency band, and through velocity and azimuth filtering of vibrations in the process of adding together time-shifted data (beam forming) (Birtill and Whiteway, 1965). Obviously, the noise is not suppressed wholly through these filtering methods, which lead to undesirable effects such as spurious detections, unreliable identification of transverse phase arrivals, etc.

Further opportunities for noise suppression can be obtained through the exploitation of differences in the polarization characteristics of the noise and signal. It is well known that longitudinal and transverse waves display high rectilinearity, whereas noise vibrations are accompanied by ground particle movements that are close to circular. In order to measure such polarization characteristics as the degree of rectilinearity of wave polarization and the azimuth and angle of incidence of the seismic ray at the recording point, it is necessary to use three-component sensors installed at three points on a circle of 1.5 km diameter and one point at the center of a NORESS array, together with other arrays of similar type (ARCESS, GERESS).

In earlier works related to the use of three-component data in arrays (Swanger *et. al.*, 1992; Jurkevies, 1988; Jepsen and Kennet, 1990), the accent was placed on polarization analysis of longitudinal and transverse waves detected previously through standard beam forming procedure. Ultimately, the purpose of this work was to improve the location capacity of the array and not to lower the detection threshold in real-time data processing. This paper proposes a new method of real time processing of data from regional arrays of the NORESS type, using polarization filtering as an additional means of suppressing noise and identifying secondary phases of the signal.

Having experience of using polarization analysis and filtering of seismic waves at a single-site three-component station (Kedrov and Bashilov, 1975; Kedrov *et. al.*, 1989a,b; Kedrov and Ovtchinnikov, 1990), and preliminary ones at the seismic array (Kedrov and Permyakova, 1994), allows the positing of a general formulation of the proposed processing algorithm as follows (fig. 1):

1) we consider $N$ three-component sensors of an array;
2) linear-phase band pass frequency filtering of the three-component records is carried out in $M$ bands;
3) polarization filtering is applied separately to each of the $N$ three-component sensors in each of the $M$ frequency bands. This procedure is performed with back-azimuth to the source $a$ and angle of incidence $i$ of the $P$-wave at the recording point, which are rigidly adhered to in the process for forming each of $L$ beams; the angles $a$ and $i$ selected by such way are theoretical ones in the preposition that seismic source is placed in the point of the Earth to which to tune the array. Through this procedure the original traces $Z$, $X(NS)$, $Y(EW)$ are transformed into full-shift traces of $P$, $SV$, $SH$ waves in the direction of each beam;
4) $L$ beams are formed from the $P$, $SV$ and $SH$ phases by adding the data from the $N$ sensors separately in each of the $M$ frequency bands;
5) signal detection is carried out on the $L*M$ $P$, $SV$ and $SH$ traces. Subsequent processing destined to determine the source parameters does not differ from the method used now in arrays of this type.

Thus the basic difference between the proposed procedure and the one used now is that each three-component sensor is oriented to the same points in space as the array is oriented to the beam forming procedure. At the same time polarization filtering of the $P$, $SV$ and $SH$ traces oriented to the beams is carried out in order to suppress noise and signals from other directions.

In this paper we have used the polarization filter proposed by E. Flinn, which operates on a well-known principle (Flinn, 1965; Archambeau and Flinn, 1965). In this method a covariance matrix $M$ is employed to obtain a quantitative measurement of the rectilinearity and direction of ground movement with respect to the recording point.

$$M = \begin{vmatrix} \mathrm{cov}(x,x) & \mathrm{cov}(x,y) & \mathrm{cov}(y,z) \\ \mathrm{cov}(y,x) & \mathrm{cov}(y,y) & \mathrm{cov}(y,z) \\ \mathrm{cov}(z,x) & \mathrm{cov}(z,y) & \mathrm{cov}(z,z) \end{vmatrix} \qquad (2.1)$$

The quadratic form (ellipsoid) given by this matrix is reduced to principal axes. The matrix $M$ has eigenvalues $L_1$, $L_2$ $L_3$ ($L_1 > L_2 > L_3$) and corresponding eigenvectors $e_1$, $e_2$ and $e_3$. The longest axis of the ellipsoid shows the orientation in space of the complete vector in the wave by angles $a$ and $i$, while the ratio of the intermediate to the major semi-axes shows the degree of elongation of the ellipsoid, *i.e.* the level of polarization rectilinearity in the wave.

Polarization filtering of the initial $Z$, $X$, $Y$ traces in the direction of the source means, in effect, calculating new reciprocally orthogonal $P$, $SV$ and $SH$ traces using the known angles $a$ and $i$ for the source in question. The obtained traces are multiplied by a weighting function $G$ in order to suppress waves with a low level of rectilinear polarization (linearity operator $G_1$) or arriving from other sources (directivity operator $G_2$):

$$G = G_1 * G_2, (0 < G < 1) \qquad (2.2)$$

$$G_1 = 1 - (L_2/L_1) \qquad (2.3)$$

$$G_2 = d * e_1 \qquad (2.4)$$

where $d$ vector is the real direction to the source. Operator $G_1$ is common to the longitudinal and transverse recorded waves and operator $G_2$ is calculated separately from formula (2.4) for $P$, $SV$ and $SH$-type waves: $G_{2P}$, $G_{2SV}$ and $G_{2SH}$. In order to control the sharpness of focus of the polar

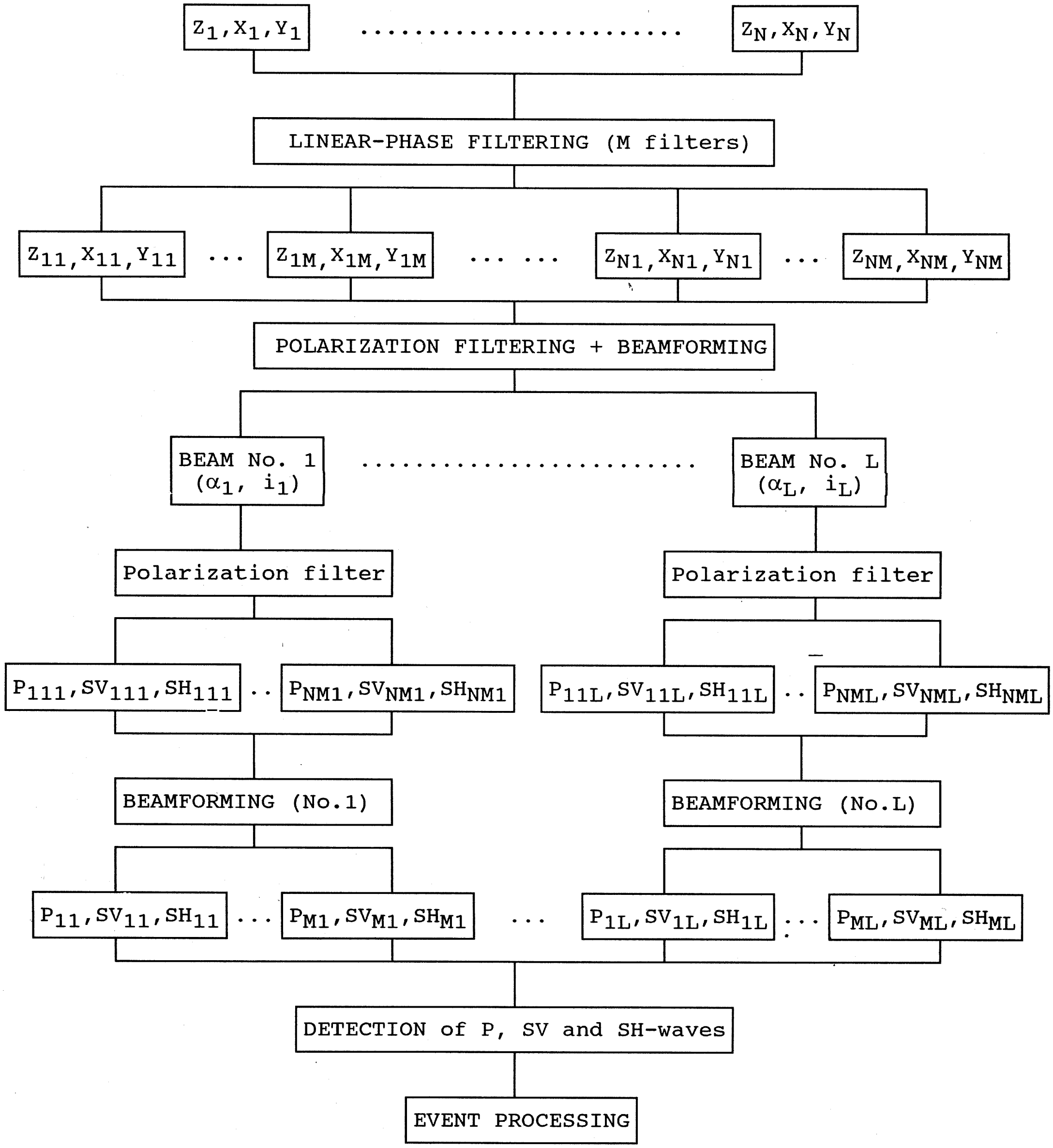

**Fig. 1.** Block diagram of the algorithm for data processing from regional arrays equipped by three-component sensors.

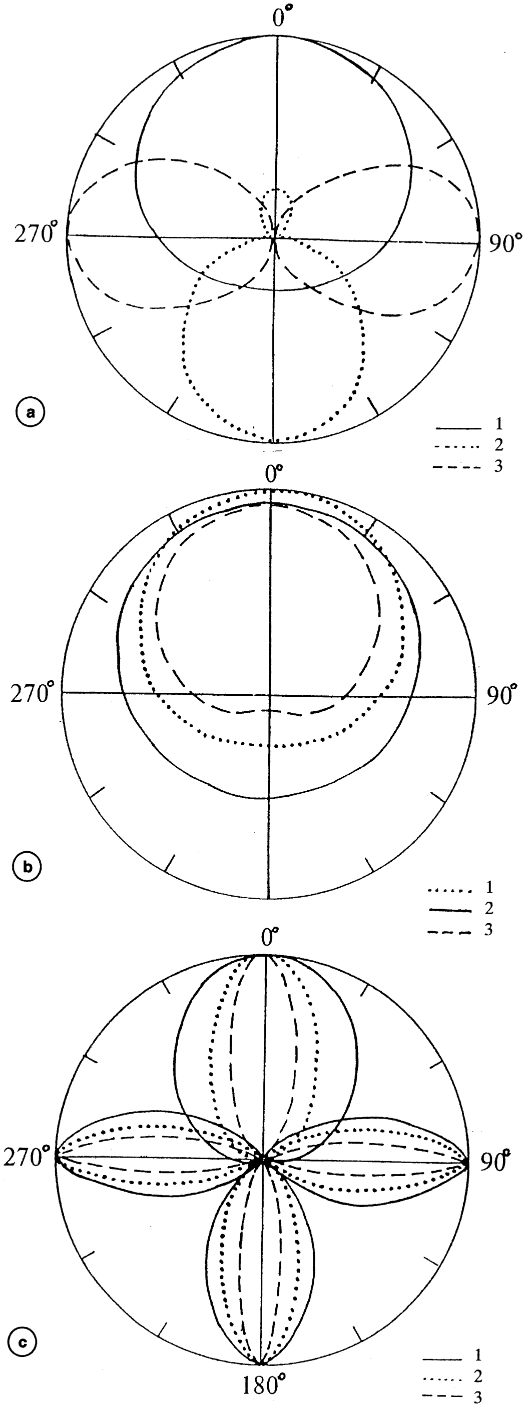

diagram as $G$, it is taken in the form

$$G = G_1^{\gamma} G_2^{\xi} \tag{2.5}$$

where $\gamma$ and $\xi$ are experimentally chosen constants.

So, once these procedures are carried out, the resulting $P_f$, $SV_f$ and $SH_f$ traces will be recorded as follows:

$$\left.\begin{aligned} P_f &= P\,G_1^{\gamma}\,G_{2P}^{\xi} \\ SV_f &= SV\,G_1^{\gamma}\,G_{2SV}^{\xi} \\ SH_f &= SH\,G_1^{\gamma}\,G_{2SH}^{\xi} \end{aligned}\right\} \tag{2.6}$$

The polar diagrams (*PD*) of the polarization filter (*PF*) for the *P*, *SV* and *SH* waves are shown in fig. 2a-c. Figure 2a shows the azimuth *PD* when the *PF* is tuned to receive the *P*, *SV* and *SH* waves from a source with parameters $a = 0°$ and $i = 30°$. We consider the case when $G_1 = 1, \gamma = 1$, $\xi = 1$, and $i_{\text{obs}} = 30°$. In practice this *PD* shows how strongly *P*, *SV* and *SH* waves received from other directions are suppressed if the *PF* is tuned to receive *P*, *SV* and *SH* waves from a specified source.

The azimuth polar diagrams shown in fig. 2b lead to the conclusion that *PF* effectively identifies records of the *P*-wave from a given source if the azimuth error $\delta a < 15°$, and records of the SV and *SH* waves if $\delta a < 10°$. Figure 2b shows the azimuth *PD* of the *P* wave if the *PF* is tuned to the source ($a = 0°$, $i = 30°$) (1) and for cases when the error $\delta i$ is $-15°$ (2) and $+15°$ (3). This example shows that $\delta i$ should not exceed 10° for *P*-wave. However it should be

**Fig. 2.** Azimuth polar diagrams of polarizing filter for: a) *P*, *SV* and *SH* waves when the array is oriented towards a source with the parameters $a = 0°, i = 30°; G_1 = 1, \gamma = 1, \xi = 1$; b) *P* wave when the array is oriented towards a source with the parameters $a = 0°, i = 30°$ (1) and errors of $\delta a = -15°$ (2) and $+15°$ (3); $G_1 = 1, \gamma = 1, \xi = 1$; c) *P*, *SV* and *SH* waves when the array is oriented towards a source with the parameters $a = 30°$, $i = 30°$ for $\xi$ values of 5 (1), 10 (2) and 50 (3); $G_1 = 1$, $\gamma = 1$.

borne in mind that in practice the degree of rectilinearity in $P$ and $S$ waves, particularly in the case of weak signals, is comparatively low ($G_1 = 0.7$-$0.8$), and then the permissible variation in $\delta a$ will be somewhat lower than the values given above.

The sharpness of focus of the azimuth *PD* can be regulated using the parameters $\gamma$ and $\xi$. Figure 2c shows how the shape of the *PD* changes with $\xi = 5$ (1), 10 (2), 50 (3); $\gamma = 1$. This example shows that the direction operator $G_2$ can be an effective means of detecting weak signals if the azimuth and distance to the source are known with enough accuracy.

At the same time it is well known that the polarization rectilinearity of $P$ and $S$ waves depends on the S/N ratio (Kedrov *et al.*, 1989a), and in the case of weak signals this can increase the amplitude of the detected wave.

Figure 3 shows theoretical estimates of the dependence between the S/N ratio for *P*, *SV* and *SH* waves and the parameters $\gamma$, $\xi$ and $G_1$ controlling the sharpness of focus of the *PD*. We consider the case when the *PD* is oriented towards the source ($a = 0°$, $i = 30°$), the signal has parameters $a = 30°$, $i = 30°$, $G_1 = 0.7$ and the noise has $a = 60°$, $i = 40°$, $G_1 = 0.5$. The initial values for the signal and noise amplitude in the *P*, *SV* and *SH* components are equal to 1. The functions given in fig. 3 lead to the conclusion that in carrying out sharply focused polarization filtering it is advisable to have $\gamma \leqslant 2$ and that the value of $\xi$ affects the S/N ratio of *P, SV* and *SH* waves in different ways. It is accordingly necessary to be able to assign different values to $\xi$ for *P*, *SV* and *SH* waves.

The value of $\xi$ is selected in accordance with the specific aims and conditions of the data-processing operation, and can reach high levels if the angles $a$ and $i$ for the given source-station path are known with sufficient accuracy for the method's capacity to discriminate. In particular, it is desirable to use large values of $\xi$ when a previously calibrated region has been monitored. If, on the other hand, detection of sources from any region is carried out, then in accordance with the algorithm proposed in this paper, the value of $\xi$ chosen will depend on the maximum possible azimuth error between the beam and the actual direction to the source.

In arrays of the NORESS type, beam forming is carried out with an azimuth step of 60°, and consequently $\delta a$ can vary between 0° and 30°, depending on the position of the epicenter of the event in question. However, in practice, $\delta a$ can reach higher values if local geological conditions at the site of each three-component sensor affect the direction of approach of the seismic ray. Obvious ways of reducing $\delta a$ and $\delta i$ due to these factors are to increase the number of beams formed and to calibrate the azimuth of the signal propagation paths with the aim of determining corrections to the azimuth and angle of incidence (or $dT/d\Delta$).

## 3. Analysis of results

To check the effectiveness of the proposed method, the NORSAR center considered a series of earthquakes with epicenter at regional distances from the NORESS and ARCESS arrays (table I), the source parameters being derived from IMS data.

During the analysis of the records of these earthquakes, attention was focused on the problem of detection $S_n$ and $L_g$ waves from regional events. To illustrate the potential of the proposed method, we consider below the efficiency of $P_n$ and $S_n$ waves detection from earthquake n. 2 ($\Delta = 17.8°$), and $P_n$ and $L_g$ wave detection from earthquake n. 7 ($\Delta = 9°$) (table I).

Figure 4a,b shows the result of summing separately the $Z$, $X$ and $Y$ components from the original records of earthquake n. 2 produced by the four three-component sensors in the ARCESS array without using a polarization filter. The lower part of the figure shows graphs of STA/LTA for the three-components $Z$, $X$ and $Y$. Figure 5a,b shows the result of processing earthquake n. 2 using the proposed method, *i.e.* polar-

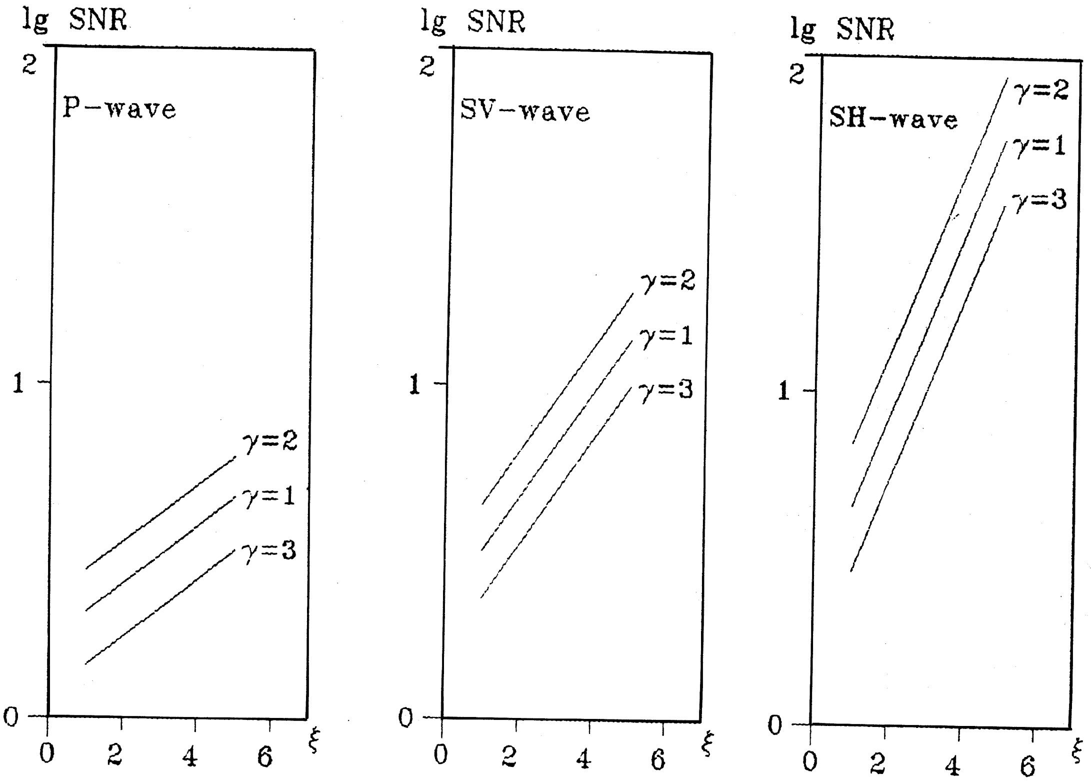

**Fig. 3.** Theoretical dependence of the S/N ratio for *P*, *SV* and *SH* waves on the parameters $G_1$, $\gamma$ and $\xi$ when the array is oriented towards a source with the parameters $a = 0°$, $i = 30°$; signal parameters: $G_1 = 0.7$, $a = 30°$; noise parameters: $G_1 = 0.5$, $a = 60°$, $i = 40°$.

**Table I.** Earthquake source parameters from IMS data, selected for analysis.

| N. | Date | $\varphi$, *N* deg | $\lambda$, *E* deg | Time at source | $M_L$ |
|---|---|---|---|---|---|
| 1 | 01.03.91 | 72.16 | 126.80 | 01:57:03 | 5.20 |
| 2 | 28.10.91 | 55.44 | 50.13 | 19:34:50 | 3.53 |
| 3 | 28.12.91 | 55.79 | 91.30 | 09:08:03 | 4.01 |
| 4 | 26.01.92 | 64.66 | 56.92 | 13:37:27 | 2.54 |
| 5 | 14.04.92 | 65.31 | 52.62 | 18:39:29 | 2.43 |
| 6 | 05.10.92 | 51.54 | 177.69 | 18:58:56 | 4.62 |
| 7 | 19.09.92 | 66.04 | 48.09 | 21:34:30 | 2.23 |
| 8 | 05.10.92 | 22.14 | 96.05 | 23:00:52 | 4.16 |

ization filtering. The upper part shows the *P*, *SV* and *SH* components obtained by polarization filtering of four 3-C sensors using summation for the beam nearest the source concerned ($\alpha = 150°$, $v = 8.9$ km/s, $i = 41.7°$). The lower part gives the STA/LTA graphs. Likewise, the results from earthquake n. 7 are given in figs. 6a,b and 7a,b. The beam nearest the source ($\alpha = 90°$, $i = 31.8°$) was used. Experimentally chosen values of $\gamma = 2$ and $\xi = 3$ were used in creating the polar diagrams. The durations of the short- and long-term detector «windows» were set at 1 and 20 s respectively.

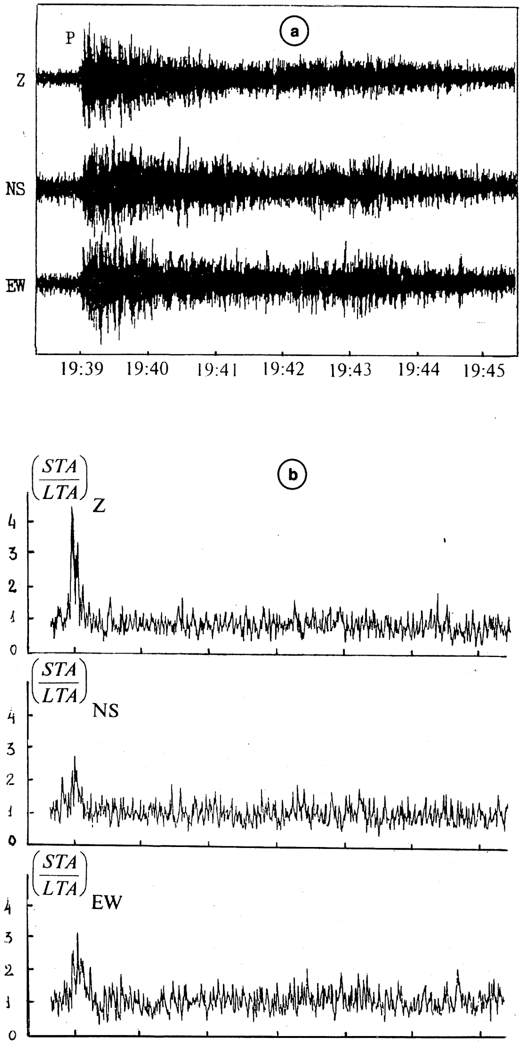

**Fig. 4a,b.** Summed *Z*, *X*, and *Y* traces obtained from four ARCESS three-component sensors for earthquake n. 2, without polarization filtering (a), and three traces from STA/LTA detector (b).

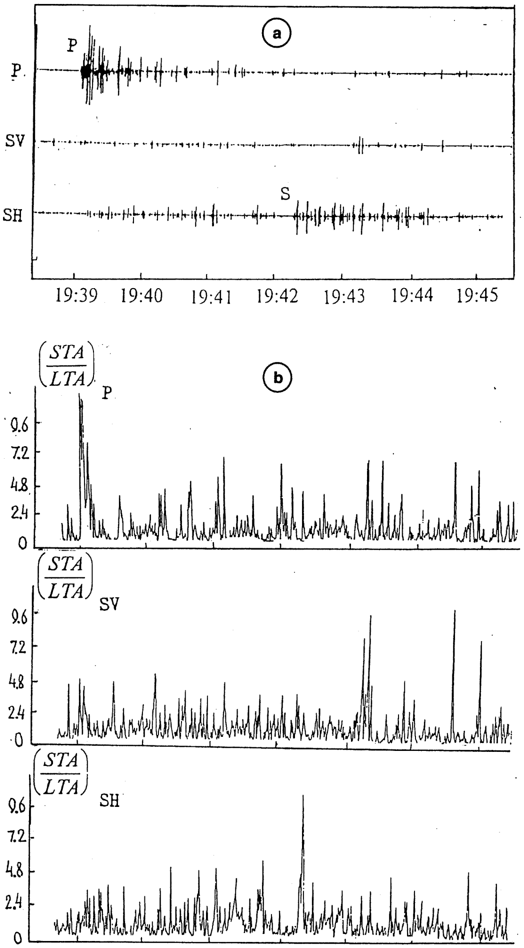

**Fig. 5a,b.** Summed *P*, *SV* and *SH* phases for earthquake n. 2 by using polarization filtering (a), and the detector traces (b).

Table II compares the traditional beam forming method (figs. 4a,b and 6a,b) with the method proposed in this paper, taking

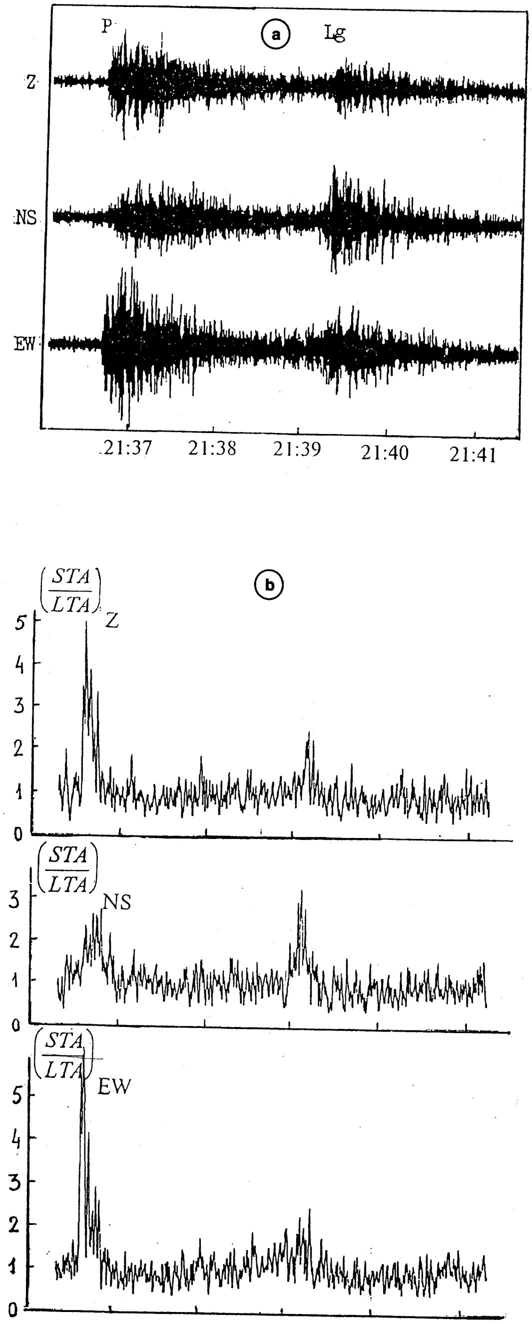

**Fig. 6a,b.** Result of processing earthquake n. 7 (ARCESS) without polarization filtering (a), and the detector traces (b).

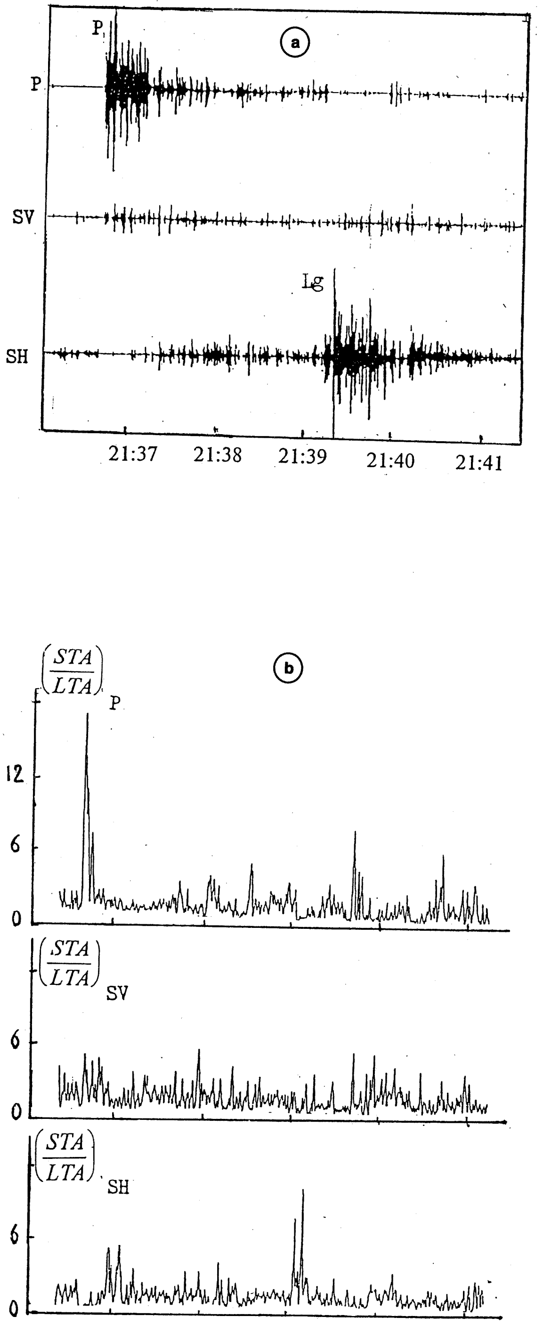

**Fig. 7a,b.** Result of processing earthquake n. 7 (ARCESS) with polarization filtering (a), and the detector traces (b).

**Table II.** Effectiveness of $P$, $S_n$ and $L_g$ wave detection using polarization filtering in the association of seismic data.

| Earthquake N. | Wave type | STA/LTA ratio | | Enhancement coefficient ($\psi$) |
|---|---|---|---|---|
| | | Beamforming without *PF* | Beamforming with *PF* | |
| 2 | $P_n$ | 4.5 | 11.0 | 2.4 |
| | $S_n$ | 2.0 | 10.5 | 5.2 |
| 7 | $P_n$ | 4.8 | 16.0 | 3.3 |
| | $L_g$ | 2.8 | 10.0 | 3.6 |

account of the polarization properties of $P_n$, $S_n$ and $L_g$ waves (figs. 5a,b and 7a,b), for the two earthquakes considered. As table II shows, the use of polarization filtering increased STA/LTA ratios by a factor of between 2.5 and 5 over the currently accepted method. Owing to the non-linear character of the polarization filtering procedure, the enhancement ($\Psi$) depends on a number of parameters of the recorded signal, notably the S/N ratio and the rectilinearity of the oscillations. These findings are preliminary and need to be refined over a representative selection of events.

As for the sequence of carrying out the procedure of polarization filtering and beam forming by the proposed method to analyze array data, the issue is a non-trivial one. On practical grounds, it would be easier to begin with beam forming from $n$ three-component $Z$, $X$, $Y$ traces and then apply polarization filtering to the summed $Z$, $X$ and $Y$ components all at ones. We feel, however, that it is of cardinal importance to begin by applying the polarization filtering procedure separately for each three-component sensor before beam forming, in order to take better into account the local geological conditions around each sensor, and thereby optimize the procedure. A practical check with earthquake n. 2 showed that when polarization filtering was applied to $Z$, $X$ and $Y$ traces previously subjected to beam forming, $P_n$ and especially $S_n$ wave detection was significantly poorer than when polarization filtering occurred first. Hence the sequence of polarizations filtering and beam forming does affect the measured amplitudes of $P$, $SV$ and $SH$ waves.

**Table III.** Angles $\alpha$ and $i$ calculated from polarization analysis of three-component records of $P$-waves from earthquake n. 2 at ARCESS and NORESS.

| Point | ARCESS | | | NORESS | | |
|---|---|---|---|---|---|---|
| | $G_1$ | $\alpha^\circ$ | $i^\circ$ | $G_1$ | $\alpha^\circ$ | $i^\circ$ |
| A0 | 0.92 | 145.4 | 44.0 | 0.89 | 92.9 | 34.2 |
| C2 | 0.88 | 135.1 | 35.7 | 0.94 | 81.2 | 28.9 |
| C4 | 0.83 | 129.4 | 39.6 | 0.96 | 96.6 | 26.1 |
| C7 | 0.82 | 140.7 | 35.5 | 0.88 | 84.1 | 30.0 |
| Average | 0.86 | 137.6 | 38.7 | 0.92 | 90.1 | 29.8 |
| SD | 0.05 | 6.0 | 3.5 | 0.04 | 6.4 | 2.9 |

Another important consideration in assessing the effectiveness of the proposed method is how strongly the *P*-wave beams deviate from the true direction and from the direction along the maximum beam. As the above mentioned theoretical estimations show the errors $\delta a$ and $\delta i$ must not exceed 15° for effective *P*, *SV* and *SH* wave detection. Table III gives the measured values of angles $a$ and $i$ at ARCESS and NORESS points A0, C2, C4 and C7 for $P_n$ waves from earthquake n. 2. Following the earlier method for analyzing three-component seismic data (Kedrov *et al.*, 1989a), the values of $a$ and $i$ were measured on the *P*-wave traces at the moment of maximum rectilinearity in the polarization of the wave ($G_1 = (G_1)_{\max}$). It should be noted that this normally occurs before maximum wave intensity is reached.

The lower part of table III gives average values for the parameters at the four points and the corresponding mean-square deviations. The NORSAR center gave values for the angles $a$ and $i$ of 126.6° and 34.4° at ARCESS and 87.4° and 30.4° at NORESS. It should also be noted that the beams used for processing this earthquake were ($a$ = 150°, $i$ = 40.7°) at ARCESS and ($a$ = 90°, $i$ = 40.7°) at NORESS. Comparison of the angles $a$ and $i$ used in polarization filtering (*i.e.* for the corresponding beams) with the true values (from NORSAR data) and those received at the three-component points in the two arrays shows that the values of $\delta a$ and $\delta i$ did not exceed the previously calculated theoretical threshold of 15°.

## 4. Conclusions

A new method of automatically processing data from NORESS-type regional seismic arrays with three-component (*Z*, *NS*, *EW*) sensors is proposed. It is based on the incorporation into real-time processing of polarization filtering in all directions where array beams are oriented ($a$, $i$).

As a result of such processing, after each beam is calculated, *P*, *SV* and *SH* traces are recorded for one or several filtered frequency bands which are further modulated by the weighting function $G = G_1G_2$ in order to suppress weakly polarized waves and waves arriving from directions other than that along which the beam lies.

Consideration of the theoretical underpinnings and experimental results reveals the proposed method to be promising, inasmuch as it displays advantages over the traditional method of beam forming:

— it increases the S/N ratio;
— it permits automatic detection and identification of different *P*, *SV* and *SH*-type phases;
— it allows the location of events to be automated using the times of arrival of $S_n$ and $L_g$ waves from weak events.

The method can also significantly increase the effectiveness of continuous seismic monitoring of a given region if the source-station path is calibrated and the parameters $a$ and $i$ used in creating sharply focused polar diagram are known with sufficient accuracy.

In the interactive mode, this method is more efficient in separating the *pP*, *sP* and *PcP* phases needed to improve estimates of source depth and investigate the source mechanism using *SV* and *SH* phases.

The findings presented in this paper are preliminary and require further elaboration and thorough statistical evaluation over a large body of experimental material.

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