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VII.5 An integrated approach to slowness analysis with arrays and three-component stations

In the past an online array detection, location and phase association procedure termed RONAPP has been developed, and it has been in routine use to analyze regional data from the NORESS array. More than one year of experience with this algorithm has shown that in some cases the azimuth estimate for P and secondary phases from the same event may differ by more than 30 degrees and therefore are not correctly associated. Fig. VII.5.1 shows a typical data set of P-Lg azimuth differences from 23 events recorded within an arbitrary three-day interval. The RONAPP results (along the vertical axis) show a considerable spread with a median value of 6.3 degrees. Whereas part of these azimuth differences may be an effect of earth structure, it should also be noted that the methods in routine use do not fully exploit the redundancy in the data. We have therefore begun a program to extend standard frequency-wavenumber analysis by incorporating a priori information applicable to three-component and possibly wideband data. We consider the matched filter as an extension of standard frequency-wavenumber analysis, and the maximum likelihood filter as an extension of "high-resolution" analysis.

As in other work, slowness solutions are inferred from a covariance matrix $\underline{\underline{C}}$. Here we introduce $\underline{\underline{C}}$ as a function of slowness $\underline{s}$ by phase shifting the signals. $\underline{\underline{C}}(\underline{s})$ has the components

$$C_{nm}(\underline{s}) = \int F_n(\omega,\underline{s})\, F_m^*(\omega,\underline{s})\, d\omega/2\pi \qquad (1)$$

where

$$F_n(\omega,\underline{s}) = F_n(\omega) \exp(i\omega\underline{s}\cdot\underline{x}_n)$$

and $F_n(\omega)$ is the Fourier spectrum at channel n.

Beamforming or matched filtering can be expressed by the normalized response

$$P(\underline{s}) = \underline{g}^+\underline{\underline{C}}\underline{g}/\{|\underline{g}|^2 \text{ tr } \underline{\underline{C}}\} \qquad (2)$$

The normalized response by the maxim likelihood method (M.L.M.) is

$$P'(\underline{s}) = \{\underline{g}^+\underline{\underline{C}}^{-1}\underline{g}\}^{-1} \cdot |\underline{g}|^2/\text{tr } \underline{\underline{C}} \qquad (3)$$

The vector $\underline{g}$ in equations (2) and (3) can take on different forms:

(a) 1-component array : $\underline{g}^T = (1, \ldots\ldots, 1)$
(b) 3-component sensor: $\underline{g}^T = (q_x, q_y, q_z)$ = displacement vector
(c) 3-component array : $g_n = q_j$, j = x, y or z.

In (a) and (c), the $\underline{\underline{C}}$ matrix is a function of slowness $\underline{s}$. In (b) and (c), the $\underline{g}$ vector is a function of slowness $\underline{s}$. In the latter case the surface interaction must be taken into account. As a consequence, 3-component results for the P phase depend on the S-velocity in an isotropic model, and results for SV depend on both the P and S velocity. Equations (2) and (3) are similar to the results of Esmersoy et al (1986), and they represent a generalization of earlier results.

Because equations (2) and (3) accomodate both array and 3-component data, they form a suitable basis for evaluating the relative performance of different methods. For the P phase we have compared wide-band to single frequency processing, array to 3-component processing, and beamforming or matched filtering to the high resolution or maximum likelihood method. NORESS records from five events at the same location in the Leningrad region provide a suitable data base for this purpose. A typical example of 3-component records from one of these events is shown in Fig. VII.5.2. Results are summarized in Figs. VII.5.3, VII.5.4 and VII.5.5. An additional result, obtained with a different data set, is given in Fig. VII.5.1.

One inference to be drawn from Fig. VII.5.1 is that, when applying beamforming or some other phase adjusting operation, more stable results are obtained by employing a wider frequency band, provided the signal-to-noise ratio is adequate over the band and the phase shifts are introduced consistently (i.e., frequency dependent). Based on the results of Figs. VII.5.3, VII.5.4 and VII.5.5, a summary concerning the relative performance of a 1-component array and a 3-component sensor is given in Table VII.5.1. It should be noted here that, whereas M.L.M. gives an apparently higher resolution for all configurations considered, for location purposes the stability of the solution is more important. Fig. VII.5.5 demonstrates that the best results for P are obtained by conventional (wide-band) beamforming of a vertical component array. Fig. VII.5.5 also shows that not only are the 3-component solutions less stable, they are also site dependent.

Our conclusions at this moment are based only on P data. Equations (2) and (3) are equally applicable to S, Lg and other phase types, but the signal model is more complicated. Fig. VII.5.6 shows preliminary results when applying S models to a section with Lg records of a four-element array of 3-component stations. The results are consistent with the NORESS solution. However, several aspects require further investigation.

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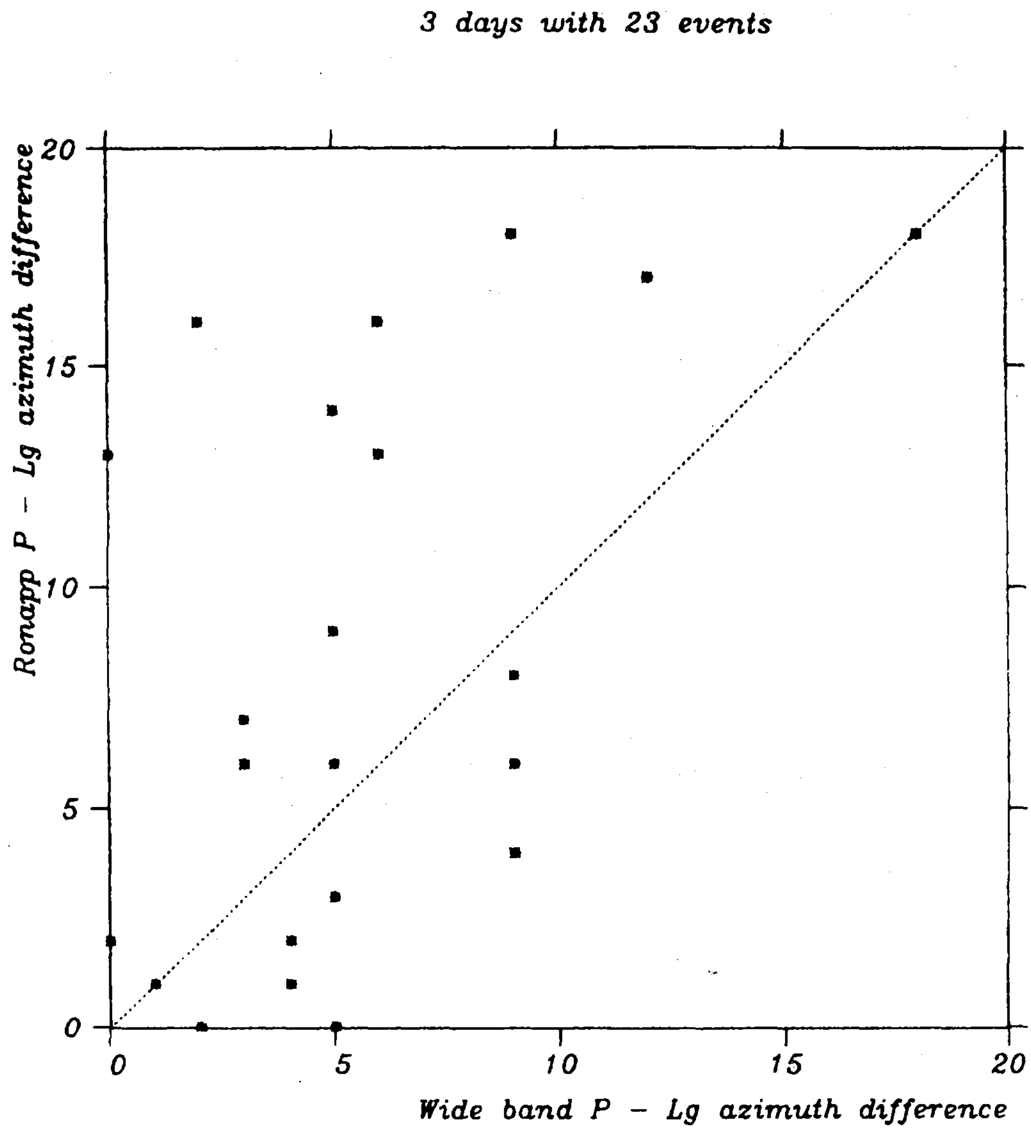
Reference

Esmersoy, C., V.F. Cormier and M.N. Toksöz (1986): Three component array processing. In: The VELA Program, Ed. A.U. Kerr, DARPA.

1-comp. array	3-comp. sensor
Principle:	
Employs phase differences	Employs amplitude ratios
Resolution increases with frequency	Resolution frequency independent
Solution averaged over array plane	Solution for one site
Solution model independent	Solution model dependent
Practice:	
Good coherence on same component	Less coherence between different components
Solutions consistent	Solutions less consistent
M.L.M. less efficient	M.L.M. more efficient

Table VII.5.1



Median (Wide Band) - 4.3

Median (Ronapp) - 6.3

Fig. VII.5.1 P-Lg azimuth difference measured by two different methods: The wide-band method versus the RONAPP procedure.

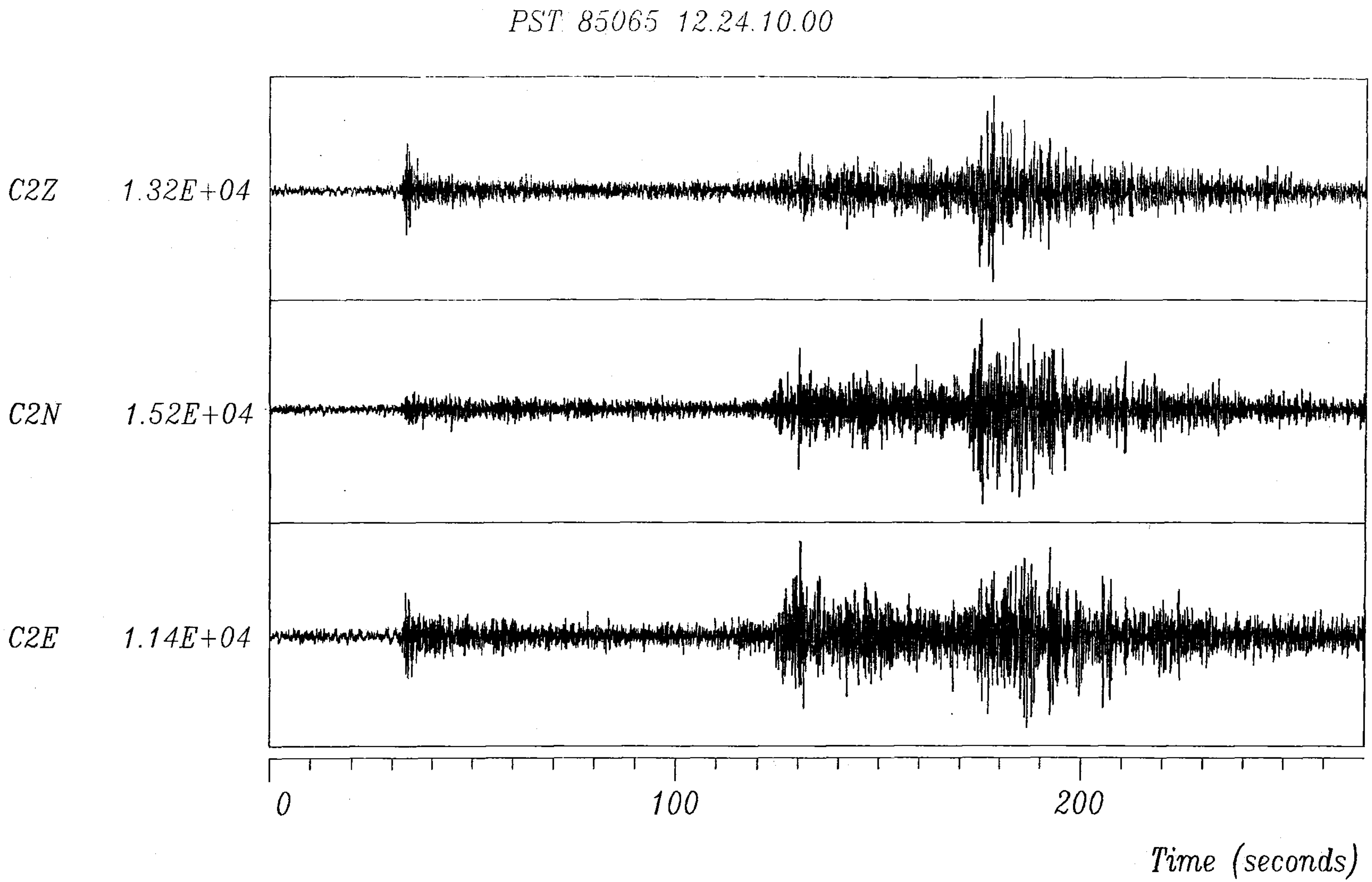


Fig. VII.5.2 Typical three-component records from event in Leningrad region. Scaling factors of different components are shown to the left.

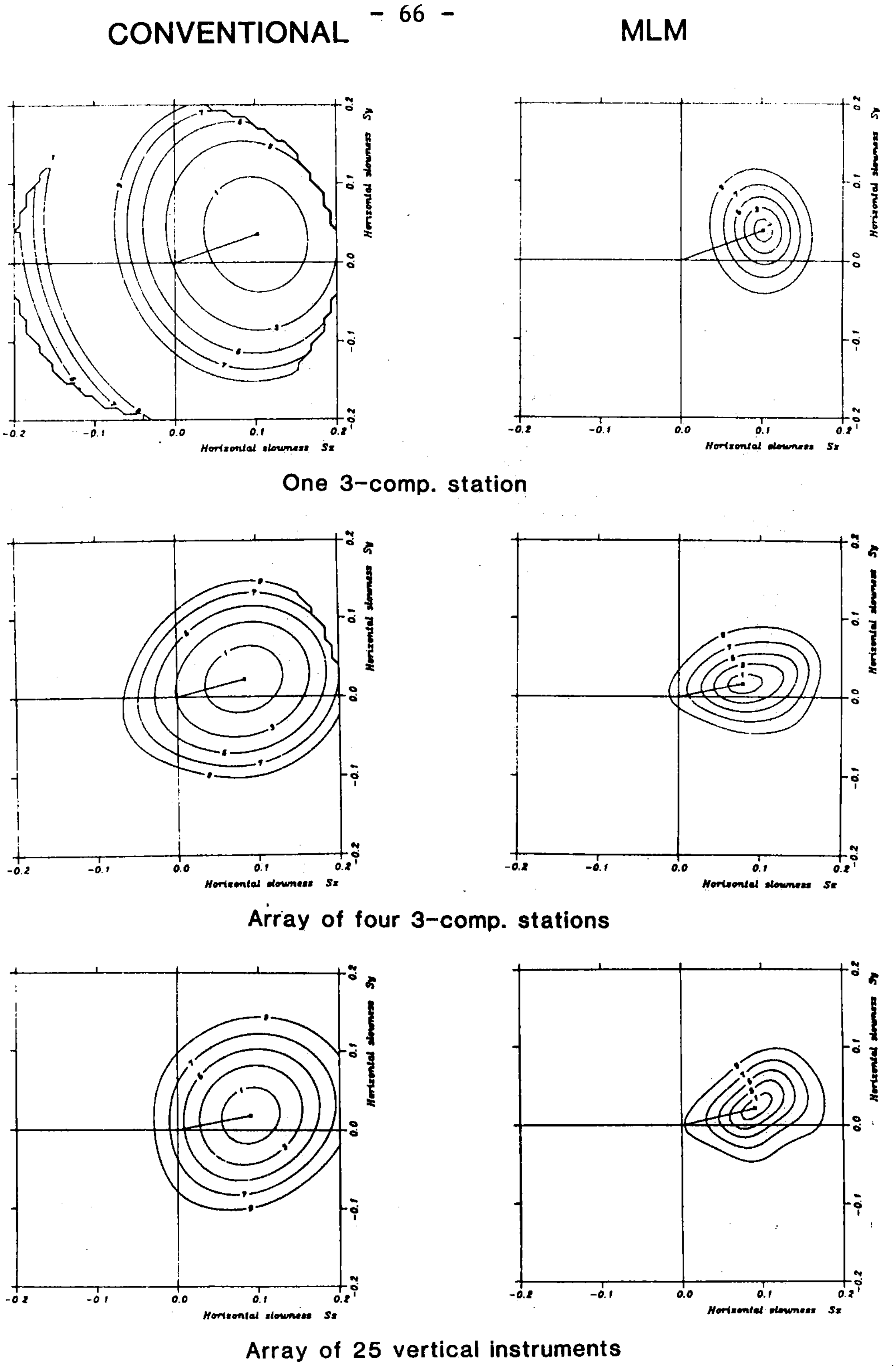


Fig. VII.5.3 Slowness response of P phase from Leningrad event processed by conventional wide-band method, and by maximum likelihood method (MLM). Results for one 3-component station, for an array of four 3-component stations, and for an array of 25 vertical component stations (the NORESS array). Slowness in s/km.

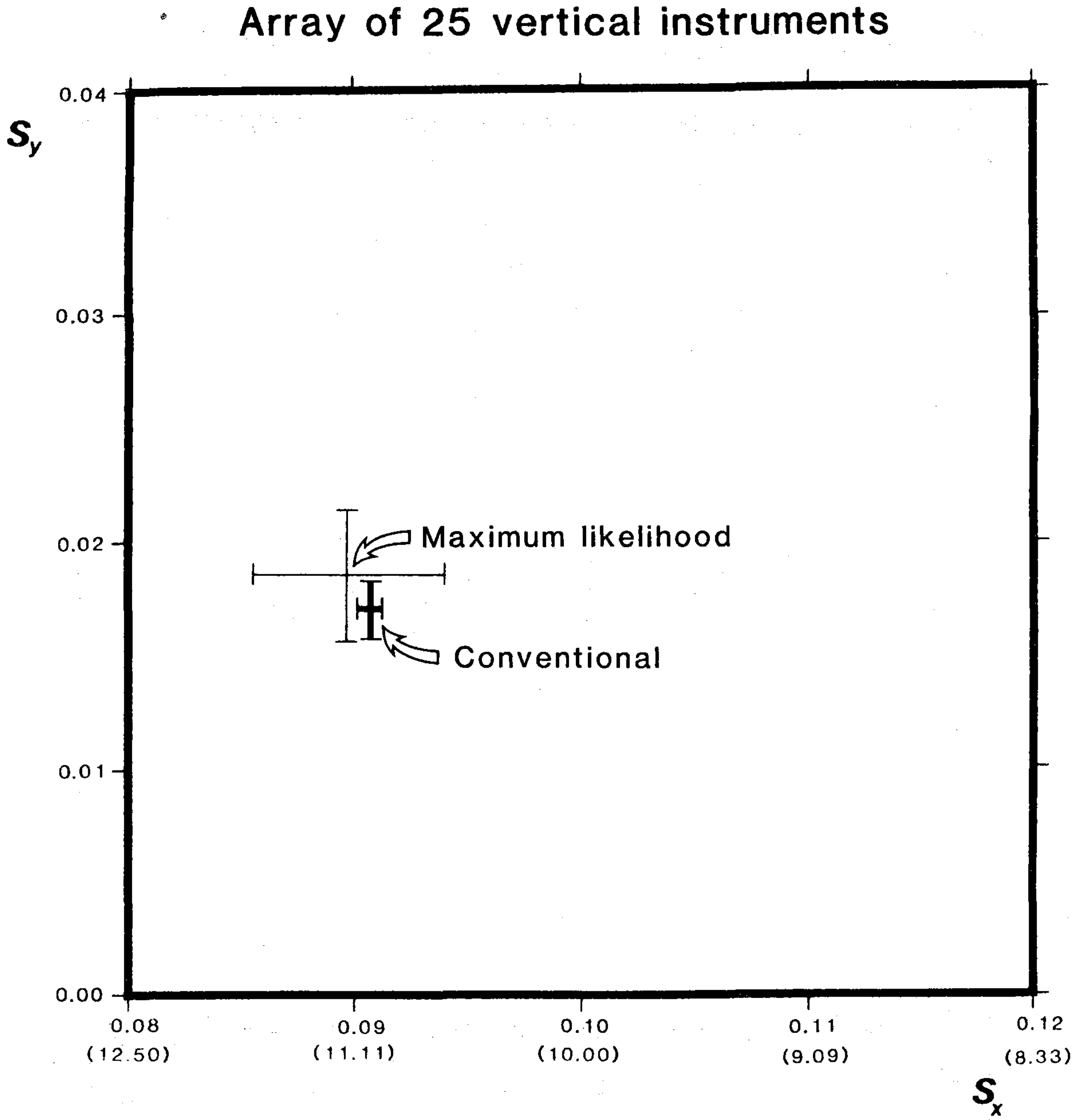


Fig. VII.5.4 Slowness results for P phase from 5 events in the same location (Leningrad region). Bars denote standard deviations. Solutions by conventional wide-band method and by maximum likelihood method.

5 events from the same location

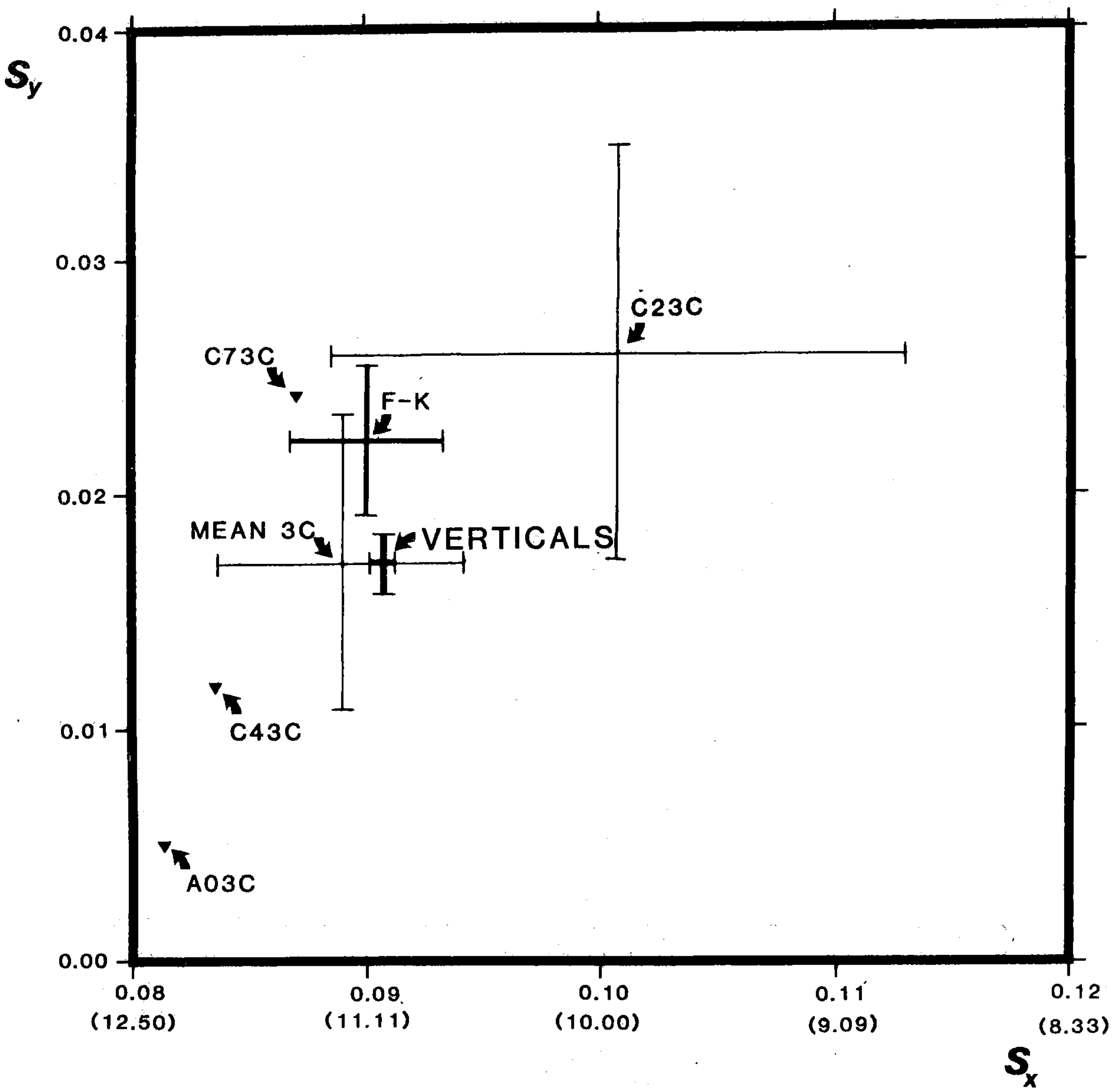


Fig. VII.5.5 Slowness results for P phase from 5 events in the same location (Leningrad region). Bars denote standard deviations. VERTICALS: wide-band solution with vertical component NORESS array. F-K: RONAPP solution with same array. A03C, C23C, C43C, C73C: 3-component solution for individual sites: st. dev. is given only for C23C, but results for the other sites are comparable. MEAN3C: mean of 3-component solutions for the 4 individual sites.

Array of four 3-component stations

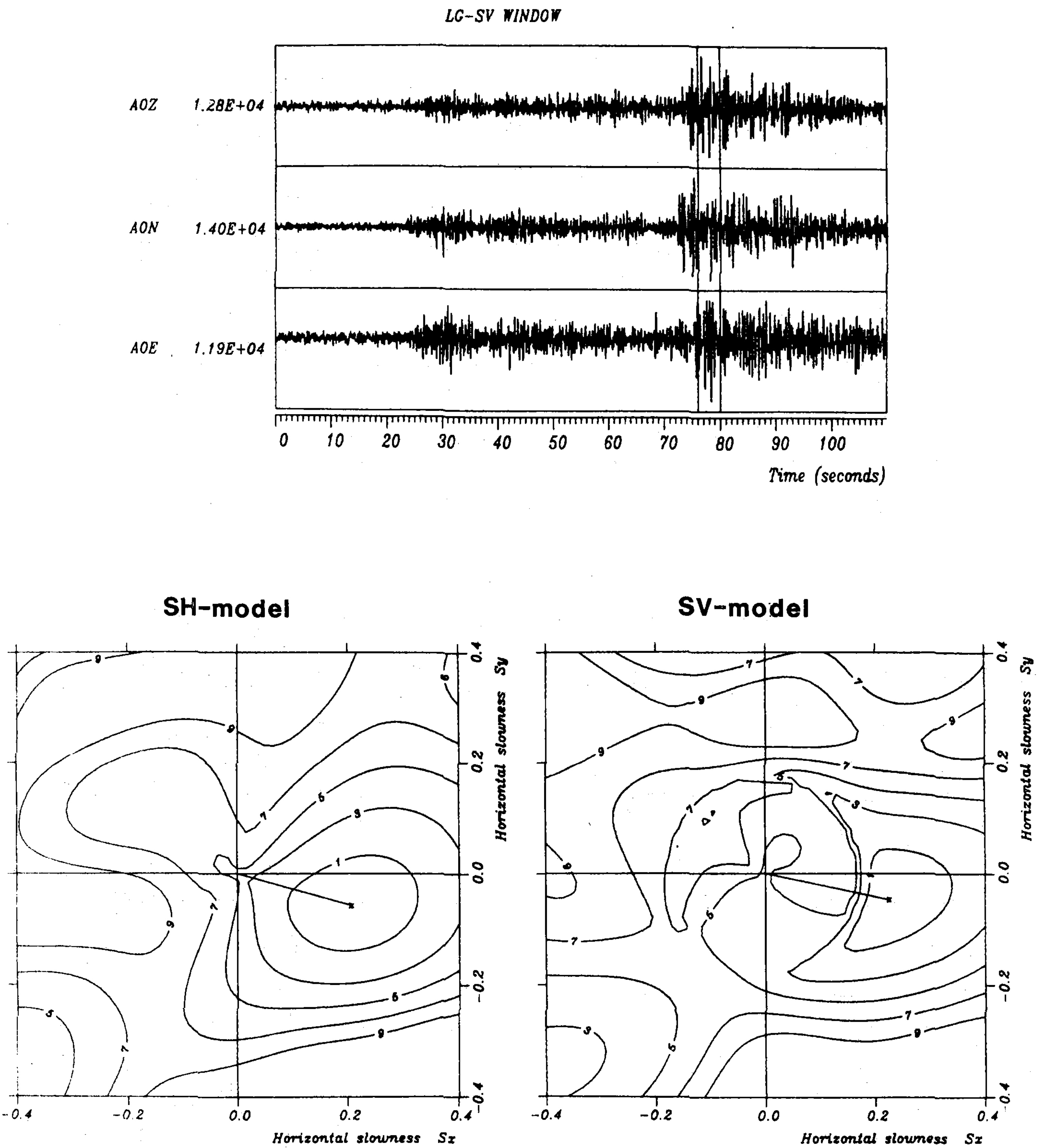


Fig. VII.5.6 Slowness response for given time section with Lg from Leningrad event. Wide-band method applied to array of four 3-component stations. Separate solutions for SH and SV type motion.