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VII.6 Towards an optimum beam deployment for NORESS; experiments with a North Sea / western Norway data base

Several of our previous investigations have addressed the problem of determining the number and type of beams needed for adequate detection of signals recorded on NORESS. For example, Kværna and Mykkeltveit (1986) arrived at a recommendation for an optimum beam deployment for detection of regional and teleseismic P-waves.

As described in several papers, e.g., Mykkeltveit and Bungum (1984), automatic determinations of event epicenters using our on-line processing package requires detection and identification of both P- and S-arrivals from each event. This study utilizes data from a fairly extensive data base of regional events recorded at NORESS, and we attempt to determine an optimum beam deployment with respect to detection of all phases from these events.

Data base and detection processing

The data base comprises 101 events from the North Sea / western Norway region with locations as shown in Fig. VII.6.1. These events were located by the western Norway network and/or the network operated by the British Geological Survey. The epicentral distance range from NORESS is 250 - 1100 km, and the magnitudes are between 1.6 and 4.2.

This event data base comprises well located events for which it is possible to accurately define the types of observed phases and to read their onsets manually, as illustrated in Fig. VII.6.2.

All events were subjected to detection processing by a large beam set using a new program system developed at NORSAR (Fyen, 1987). Distributed among 12 different filter bands, this beam set contained 72 steered beams for detection of P-waves, 132 beams for detection of S-waves, 12 incoherent beams made from the vertical channels and 12 incoherent beams made from the horizontal channels. In selecting this beam set we attempted to include all candidates that could conceivably contribute to increasing the detection capability. A description of this beam set is given in section VII.3 of this report (Kværna et al, 1987).

The output from the detection analysis is a report containing parameters such as an identification of the detecting beam, detection time, STA, LTA and STA/LTA (SNR). For all events, the detection reports were divided into Pn, Pg, Sn and Lg detections. Table VII.6.1 shows an example of a report where the different detections are identified.

The essence of the following is a strategy for determination of a beam set that meets certain performance criteria and at the same time contains the lowest possible number of beams, selected from the set of 228 beams described above.

Analysis procedure

In the work presented in section VII.3 of this report (Kværna et al, 1987), we attempted to infer the STA/LTA (SNR) detection thresholds of the respective beams from noise statistics. For each phase detected in the present investigation, these thresholds were used to create a basis for comparison between the different beams. The procedure for comparing the maximum SNR values can be illustrated by the following example:

i) Assume that a Pn phase is detected by three different beams,

by beam A, with a maximum SNR of 26.0 dB,
by beam B, with a maximum SNR of 23.5 dB and
by beam C, with a maximum SNR of 22.0 dB.

ii) Assume that the detection thresholds inferred from noise statistics are,

for beam A, 12.0 dB
for beam B, 10.0 dB and
for beam C, 6.0 dB

iii) If we take the detection thresholds to represent a common basis for comparison, a unified quality measure of the maximum SNR values will be the number of decibels exceeding these thresholds. These quality measures, from now on referred to as 'the adjusted SNR values', will for the three beams in this example be:

Adjusted SNR value for beam A: (26.0 - 12.0) dB = 14.0 dB.
Adjusted SNR value for beam B: (23.5 - 10.0) dB = 13.5 dB.
Adjusted SNR value for beam C: (22.0 - 6.0) dB = 16.0 dB.

From this we conclude that beam C is the 'best' beam for detecting this particular Pn phase.

Rather than progressing in our investigation with the concept of a 'best' beam, we introduce the concept of a 'valid' beam or 'valid' detection: The maximum obtainable SNR value of a detection will be reduced by phenomena like mis-steering of the coherent beams, random increase in the noise level and lowered data quality on single channels. We therefore decided that all detections with adjusted SNR values within 3 decibels of the best adjusted SNR for the phase, were to be counted as 'valid' detections. This implies that each detected phase will have several possible candidates for the 'best' beam.

The 3 decibels acceptance level is chosen rather subjectively, however, the coherent beam deployment is sufficently dense that signal losses due to mis-steering are within 3 decibels. In later analyses, this acceptance level can of course be reduced or increased.

Table VII.6.2 shows the maximum SNR values and corresponding adjusted SNR values for one of the Pn-phases in this investigation, for all 48 beam types.

Results

After finding the 'valid' detections for all phases in the data base of 101 events, we were in a position to evaluate which beams should be included in the optimum deployment. Tables VII.6.(3a-3d) show the 'valid' detections for all Pn, Pg, Sn and Lg-phases, respectively.

When considering the Pn phase in Table VII.6.3a, we found that beam number 10 had the maximum number of 'valid' entries, 60 out of a total number of 98. From this we concluded that this beam should obviously be included in the final beam deployment. An interesting observation was that many of the Pn phases from the North Sea / western Norway region had dominant signal frequencies above 10 Hz.

Beam number 6 had the highest number of 'valid' detections for the Pg phase, see Table VII.6.3b. For the Sn phase, (Table VII.6.3c), beam number 45 or 46 was an obvious candidate. Beam number 46 had 66 'valid' entries, which is about 80% of the total number of Sn detections.

Like the Pn phase, the Sn phases from this region contain much energy at high frequencies.

For the Lg phase (Table VII.6.3d) no specific beam is an obvious candidate for inclusion in the recommended beam deployment. Beam 42, however, exhibits the highest number of 'valid' entries.

In order to find the optimum beam deployment, we attempted to group the beams together in various ways. We required that all (or almost all) detected phases should be represented by at least one 'valid' beam in the final deployment. First, we attempted to do the grouping for each phase type individually.

For the Pn-phase, the number of 'valid' entries for the various beams are given in the last column of Table VII.6.3a. We first select the beam with the highest number of 'valid' entries, in this case beam number 10, and that beam handles 60 of the detected Pn-phases. Next, beam number 6 accommodates 22 of the remaining 38 beams, and so on. By iteration, we ended up with a priority list of beams as given in Table VII.6.4a.

From this we can infer that 8 beams are required to cover all Pn phases, but 5 beams alone cover 96% of the 'valid' entries. Note that, e.g., beam 10 (10.0 - 16.0 P) includes eight coherent beams with different steering delays. The actual azimuth range for this data base is 180-360 degrees, so it is sufficient to distribute about 4 coherent P-beams in each filter band to span this area. If we in addition accept that it is sufficient to cover 96% of the valid detections, the optimum beam deployment for detecting Pn-phases from this specific region will contain 16 coherent P-beams and one incoherent beam made from the vertical channels. If we require the coherent beam deployment to span all azimuth directions (symmetrically), about 32 coherent P-beams must be included.

The beam priority lists for the Pg, Sn and Lg phases are given in Tables VII.6.4b-d, respectively.

An interesting observation is the large number of beams required to cover the Pg detections. From Tables VII.6.4a-d we can infer the beam deployment required for optimum detection under the given requirements, when treating the phases individually; see Table VII.6.5.

When recommending specific beam deployments, it is important to keep in mind the implications on computational load for the on-line processor. This load is primarily determined by the total number of traces that must be bandpass filtered, and the number of beams that are created.

For processing the data with the deployment of Table VII.6.5, 178 single channels must be filtered, and 55 beams must be formed, each of which is subjected to STA/LTA-type detection processing.

These numbers can be considerably reduced if we apply an algorithm where all phases are treated at the same time. We first include the most obvious beam candidates (beams no. 46, no. 10, no. 42 and no. 6), and then start the interative sorting procedure. The results from this procedure are given in Table VII.6.6. Compared to the numbers in Table VII.6.5, the size of the beam deployment is reduced by 30-40%.

As a final experiment, we decided to exclude the coherent S-beams from the analysis. The results are given in Table VII.6.7. Compared to the results given in Table VII.6.6, the number of beams to be formed were marginally reduced, but the number of traces to be filtered were increased due to including more incoherent beams made from the vertical channels.

Conclusion

For detection of Pn-phases from the North Sea / western Norway region, the high frequency coherent P-beams will contribute significantly to an optimized beam deployment. For the more low frequency Pg phase, the coherent P-beam filtered between 3.5 and 5.5 Hz seem to do best.

Including incoherent beams made from the horizontal channels, will improve the detectability of Sn significantly. We also found that the Sn phase in most cases had dominant frequencies around 10 Hz.

Like Pg, the Lg phase had maximum SNR in the range 1.5-4.5 Hz. Incoherent beams made from both the horizontal and vertical channels must be included for optimum detection of the Lg phase.

A tool for determining the optimum beam deployment has been developed. To validate the method and find a beam deployment that adequately covers also other relevant regions, we plan to perform similar studies for events from other areas, like the western USSR.

In our future work, then, we want to test whether the symmetric beam deployment inferred from the North Sea/western Norway data base is sufficient for optimum detection of events from other regions, or if other beam types have to be added to the beam deployment.

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S. Mykkeltveit
F. Ringdal

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Kværna, T., S. Kibsgaard and F. Ringdal (1987): False alarm statistics and threshold determination for regional event detection, Semiannual Technical Summary, 1 April - 30 September 1987, NORSAR Sci. Rep. No. 1-87/88, Kjeller, Norway.

Mykkeltveit, S. and H. Bungum (1984): Processing of regional events using data from small-aperture arrays, Bull. Seism. Soc. Am. 74, 2313-2333.

```
Manually read arrival times:

Pn: 14.11.56.4  Pg: 14.12.05.5  Sn: 14:12.39.0  Lg: 14.12.51.1

Detection results for steered P-beams.

Time interval subjected to detection processing:

017:14.09.46.0 - 14.13.46.0

Beam     Detection interval       STA     LTA     SNR  #detections

***> Pn

I0906 017:14.11.56.6 - 12.03.9  827.01  18.52  44.661   1
H0807 017:14.11.56.9 - 12.06.4  647.98  12.91  50.173   4
J1006 017:14.11.56.9 - 12.04.9  543.86  11.58  46.969   9
E0505 017:14.11.57.1 - 12.03.4  318.56  26.33  12.099   2
F0607 017:14.11.57.1 - 12.03.4  454.06  26.09  17.406   5
G0707 017:14.11.57.1 - 12.03.6  793.77  30.41  26.106   5
D0408 017:14.11.57.4 - 12.03.4  263.52  23.11  11.403   9
C0308 017:14.11.57.6 - 12.03.1  279.83  30.10   9.297  13
B0201 017:14.11.58.4 - 11.58.9  112.92  27.44   4.116   1

***> Pg

H0803 017:14.12.05.4 - 12.11.9  234.43  41.59   5.637  16
F0607 017:14.12.06.1 - 12.10.6  812.29  90.77   8.949   8
E0505 017:14.12.06.1 - 12.09.1  520.37  76.49   6.803  15
G0707 017:14.12.06.6 - 12.12.9  749.01 132.91   5.635   4
J1002 017:14.12.07.6 - 12.08.1  128.03  30.39   4.213   8
D0408 017:14.12.08.1 - 12.08.9  345.48  74.75   4.622  11
F0602 017:14.12.13.6 - 12.13.9  138.17  34.16   4.045   1

***> Sn

H0805 017:14.12.40.1 - 12.42.1  318.42  77.59   4.104   2
D0402 017:14.12.40.4 - 12.40.9  231.42  55.96   4.136   2
G0702 017:14.12.40.4 - 12.41.4  516.81  98.40   5.252   3
C0302 017:14.12.40.4 - 12.40.9  253.58  57.01   4.448   2

***> Lg

F0603 017:14.12.51.9 - 12.54.1  728.74 103.15   7.065   1
E0502 017:14.12.52.1 - 12.54.1  662.00  78.63   8.419  12
D0405 017:14.12.52.6 - 12.54.4  464.31  83.58   5.555   2
C0302 017:14.12.53.1 - 12.59.6  449.74  78.16   5.754   3
H0806 017:14.12.53.4 - 12.53.9  474.39 112.32   4.223   1
F0602 017:14.12.55.9 - 12.56.6  538.07  95.86   5.613   2
B0201 017:14.12.57.4 - 12.57.6  305.59  73.26   4.171   2
D0402 017:14.12.58.1 - 12.58.6  497.49 116.50   4.270   1
```

Table VII.6.1 The detection report shown in this table is the output from detection analysis of the event displayed in Fig. VII.6.2. We have here only given the results from processing the 3-minute time interval containing the Pn, Pg, Sn and Lg phases, with the 72 coherent beams with P-wave velocities. The beam types are identified from the first character of the beam name. The last two digits of the beam name identify the coherent beam with maximum SNR within that beam type. In the experiment outlined in this paper, we give results for each coherent beam type rather than for individual coherent beams. The last column of the detection report gives the number of detections for the beam type within the detection interval, i.e., the time interval for which the SNR values exceed the threshold.

```
Distance: 400.9 km.
Azimuth : 229.0 degrees
ML      :   2.7

Beam no.  Beam type          SNR in dB          Adjusted SNR in dB

 1        1.0 -  3.0 P:        0.00        /          0.00
 2        1.5 -  3.5 P:       12.30        /          1.29
 3        2.0 -  4.0 P:       19.37        /          6.67
 4        2.5 -  4.5 P:       21.14        /          8.74
 5        3.0 -  5.0 P:       21.66        /         10.25
 6        3.5 -  5.5 P:       24.82        /         13.91
 7        5.0 -  7.0 P:       28.34        /         16.63
 8        6.5 -  8.5 P:       34.01        /    *    22.51
 9        8.0 - 16.0 P:       33.00        /    *    24.60
10       10.0 - 16.0 P:       33.44        /    *    24.94
11        1.0 -  2.0 P:        0.00        /          0.00
12        2.0 -  3.0 P:        0.00        /          0.00
13        1.0 -  3.0 S:        0.00        /          0.00
14        1.5 -  3.5 S:        0.00        /          0.00
15        2.0 -  4.0 S:        0.00        /          0.00
16        2.5 -  4.5 S:        0.00        /          0.00
17        3.0 -  5.0 S:       15.56        /          3.26
18        3.5 -  5.5 S:       19.41        /          7.41
19        5.0 -  7.0 S:       20.82        /          8.12
20        6.5 -  8.5 S:       26.52        /         14.72
21        8.0 - 16.0 S:       28.17        /         19.17
22       10.0 - 16.0 S:       31.88        /    *    22.88
23        1.0 -  2.0 S:        0.00        /          0.00
24        2.0 -  3.0 S:        0.00        /          0.00
25        1.0 -  3.0 V:        0.00        /          0.00
26        1.5 -  3.5 V:        7.24        /          0.64
27        2.0 -  4.0 V:        0.00        /          0.00
28        2.5 -  4.5 V:        0.00        /          0.00
29        3.0 -  5.0 V:       11.43        /          4.22
30        3.5 -  5.5 V:       14.12        /          7.32
31        5.0 -  7.0 V:       18.69        /         13.99
32        6.5 -  8.5 V:       23.17        /         18.67
33        8.0 - 16.0 V:       26.63        /    *    22.63
34       10.0 - 16.0 V:       27.94        /    *    23.94
35        1.0 -  2.0 V:        0.00        /          0.00
36        2.0 -  3.0 V:        7.60        /          0.00
37        1.0 -  3.0 H:        0.00        /          0.00
38        1.5 -  3.5 H:        0.00        /          0.00
39        2.0 -  4.0 H:        0.00        /          0.00
40        2.5 -  4.5 H:        0.00        /          0.00
41        3.0 -  5.0 H:        0.00        /          0.00
42        3.5 -  5.5 H:       17.13        /         11.84
43        5.0 -  7.0 H:       15.46        /         10.36
44        6.5 -  8.5 H:       19.34        /         14.54
45        8.0 - 16.0 H:       20.00        /         16.30
46       10.0 - 16.0 H:       20.82        /         17.12
47        1.0 -  2.0 H:        0.00        /          0.00
48        2.0 -  3.0 H:        0.00        /          0.00
```

Table VII.6.2 This table gives the maximum SNR values and the corresponding adjusted SNR values for the Pn phase shown in Fig. VII.6.2. The beam types with the characters 'P' or 'S' are coherent beams with P- or S-wave velocities. The character 'V' indicates incoherent beams made from the vertical channels, whereas 'H' indicates incoherent beams made from the horizontal channels. The beam types with a star (*) in the column for adjusted SNR are 'valid' beams, i.e., within 3 decibels of the beam type of highest SNR. Beam types with the value 0.0 have not detected the phase.

```
                         10        20        30        40        50        60        70        80        90       100    #valid
No.  Beam type            !         !         !         !         !         !         !         !         !         !    entries
 1  1.0 -  3.0 P                                                       .        .                           .                0
 2  1.5 -  3.5 P                                                       .        .                           .                0
 3  2.0 -  4.0 P                    *                        *         .     *  .        *            *     .                5
 4  2.5 -  4.5 P                  * *                *  *    *         * .     *  .      * *        *  **     .               12
 5  3.0 -  5.0 P      * **   ****  *      *         *     * **         .     ** .*      *      *  **  **     .               22
 6  3.5 -  5.5 P      ************ *      *   * *   **       **        .     ** .*      * *    ** *   **   * .     *         32
 7  5.0 -  7.0 P    *  *   **   * *     * *         *  **   *   *  *   .*       .*      *       * *    *  ** .     *         23
 8  6.5 -  8.5 P        *      *        * * **        *      **  *   .* *  * *.*      *       *  *      ** .   * **        23
 9  8.0 - 16.0 P  * * * * ***        ***  *   *    **  * * ** *** ** *. *****  *.***  ***  ** **** * ***** * .  ***  **     55
10 10.0 - 16.0 P  *** * *****        ***  *  **    **  * * ******  ***  . * *** *. ***** * **** * **** ***  *.*****   *     60
11  1.0 -  2.0 P                                                       .        .                           .                0
12  2.0 -  3.0 P                                                       .        .                           .                0
13  1.0 -  3.0 S                                                       .        .                           .                0
14  1.5 -  3.5 S                                                       .        .                           .                0
15  2.0 -  4.0 S                                                       .        .                           .                0
16  2.5 -  4.5 S                                                       .        .                           .                0
17  3.0 -  5.0 S                   *                    *              .        .                           .                2
18  3.5 -  5.5 S                                                       .        .                           .                0
19  5.0 -  7.0 S                                                       .        .                           .                0
20  6.5 -  8.5 S                                                       .        .                           .                0
21  8.0 - 16.0 S                                                       .        .                           .                0
22 10.0 - 16.0 S                                             * *       . *   * *.  **      * *              .                9
23  1.0 -  2.0 S                                                       .        .                           .                0
24  2.0 -  3.0 S                                                       .        .                           .                0
25  1.0 -  3.0 V                                                       .        .                           .                0
26  1.5 -  3.5 V                                                       .        .                           .                0
27  2.0 -  4.0 V                                  *                    .        .                           .                1
28  2.5 -  4.5 V                                  *                    .        .                           .                1
29  3.0 -  5.0 V                                                       .     *  .                           .                1
30  3.5 -  5.5 V                   *                     *             .     *  .                           .                3
31  5.0 -  7.0 V                                         *             .        .        *       **   *     .      *         6
32  6.5 -  8.5 V                            *                    **    .        .              * *       *  .      *         7
33  8.0 - 16.0 V                      *     ***              * *       .       *.  *         *  *           .   *           11
34 10.0 - 16.0 V          *          *  ** *  ***              ***    *. *** * *.  **     ** *  *    * *    .  **           27
35  1.0 -  2.0 V                                                       .        .                           .                0
36  2.0 -  3.0 V                                  *                    .        .                           .                1
37  1.0 -  3.0 H                                                       .        .                           .                0
38  1.5 -  3.5 H                                                       .        .                           .                0
39  2.0 -  4.0 H                                  *                    .        .                           .                1
40  2.5 -  4.5 H                                  *                    .        .                           .                1
41  3.0 -  5.0 H                                                       .        .                           .                0
42  3.5 -  5.5 H                                                       .        .                           .                0
43  5.0 -  7.0 H                                                       .        .                           .                0
44  6.5 -  8.5 H                                                       .        .                           .                0
45  8.0 - 16.0 H                                                       .        .                           .                0
46 10.0 - 16.0 H                                                       .        .                           .                0
47  1.0 -  2.0 H                                                       .        .                           .                0
48  2.0 -  3.0 H                                                       .        .                           .                0
```

Table VII6.3 a) The 'valid' detections for all Pn phases in the data base are in this table denoted by a star (*). If a Pn phase for one of the events is not detected by any beam, the coloum is marked with a period (.). In the last column, the total number of 'valid' entries for each beam type is given.

```
                                                              Event number

                          10        20        30        40        50        60        70        80        90       100    #valid
No.  Beam type             !         !         !         !         !         !         !         !         !         !    entries

 1  1.0 -  3.0 P   . .. . .. .   ..        .   .    ....      .        .. .     *.... .      . ..    .. .           .       1
 2  1.5 -  3.5 P   . .. . .. .   ..        .   .    ....      .        .. .      .... .      . ..    .. .           .       0
 3  2.0 -  4.0 P   . .. .*.. . **..        .   .    ....*     .        ..*.   *   .... .      .*..    .. .           .*      8
 4  2.5 -  4.5 P   .*.. .*.. . **..        .   .  * ....*     * .*    *   .. .   *   .... .  *  *.*..*   .. .   *       .*     16
 5  3.0 -  5.0 P   .*.. . ..*.   ..* * **  .** .** ....       * .  * *** .. .*  *   .... .  *  *.*..**  ..*.*    * * * . *    28
 6  3.5 -  5.5 P   .*.. . ..*.   ..* ***** .** .*  *....      **. ** ****.. .** *   .... . **  *.*.. **  ..*.**    *** * .**   38
 7  5.0 -  7.0 P   .*.. . .. .   ..   *  * .   .*  *....      .     *   .. .*      .... .*      .*.. **  .. .**   ***  **.*   19
 8  6.5 -  8.5 P   .*.. . .. .   .. *    * .   .*   ....      .    *   .. .***     .... .**     .*..    .. . *    *   *.     14
 9  8.0 - 16.0 P   . .. . .. .   ..     *. *   .    ....      .        .. . *      .... .*      . ..    .. .           .       4
10 10.0 - 16.0 P   . .. . .. .   ..     *.     .    ....      .        .. . *      .... .       . ..  * .. .           .       3
11  1.0 -  2.0 P   . .. . .. .   ..        .   .    ....      .        .. .        .... .       . ..    .. .           .       0
12  2.0 -  3.0 P   . .. . .. .   ..        .   .    ....      .        .. .        .... .       . ..    .. .           .       0
13  1.0 -  3.0 S   . .. . .. .   ..        .   .  * ....*     .        .. .      **.... .       . ..   *.. .           .       5
14  1.5 -  3.5 S   . .. . .. .   ..        .   .  * ....      .        .. .        .... .     ** . ..    .. .           .       3
15  2.0 -  4.0 S   . .. . .. .   ..        .   .  * ....* *  *.        .. .     *  .... .     ** . ..    .. .  *        .       8
16  2.5 -  4.5 S  *. .. . .. .*  ..        .   .  * .... *   *.        .. .        ....*.     ** . ..    .. .           .       8
17  3.0 -  5.0 S  *. .. . .. . * ..  *     .   .    ....      * .  *     .. .     *  ....*.    *   . ..    .. . * *   **  .**    14
18  3.5 -  5.5 S  *. .. . .. *.** ..       .   . *  .... *    * .  *    **.. .     ** .... .    *   . ..    .. . * *   **  .**    19
19  5.0 -  7.0 S  *. .. . .. .*  ..        .   .    ....      .  *     .. .        .... .       . ..    .. . * **      .       6
20  6.5 -  8.5 S   . .. . .. .*  ..        .   .    ....      .  *     .. .        .... .       . ..    .. . *         .       3
21  8.0 - 16.0 S   .*.. . .. .   ..     *.     .    ....      .        .. .      *.... .       .*..    .. .           .       4
22 10.0 - 16.0 S   .*.. . .. .   ..     *.     .    ....      .        .. . **     .... .       . ..    .. .          *.       5
23  1.0 -  2.0 S   . .. . .. .   ..        .   .    ....      .        .. .        .... .       . ..    .. .           .       0
24  2.0 -  3.0 S   . .. . .. .   ..        .   .    ....      .        .. .        .... .       . ..    .. .           .       0
25  1.0 -  3.0 V   . ..*. .. .   ..        .   .    ....      .        .. .        .... .      * . ..    .. .           .       2
26  1.5 -  3.5 V   . ..*. .. .   ..        .   .    ....  *   .        .. .        .... .       . ..    .. .  *        .       3
27  2.0 -  4.0 V  *. .. . .. .   ..*       .   .    ....  *   .        .. .        .... .     *  . ..    .. .  *        .       5
28  2.5 -  4.5 V   . .. . .. .   ..*       .   .    ....  * * .        .. .        .... .    **  . ..    .. .           .       5
29  3.0 -  5.0 V   . .. . .. .   ..*       .   .    ....      .        .. .        .... .    *   . ..    .. .*  *    *  .       5
30  3.5 -  5.5 V   . .. . .. .   ..*       .   .    ....      .  *   * .. .     *  .... .    *   . ..    .. .*         * .*     8
31  5.0 -  7.0 V   . .. . .. .   ..   *  **.  *.*   ....   *  . **   * .. .     *  .... .   *    .*..*   .. .*   * *    .  *   17
32  6.5 -  8.5 V   . .. . .. .   ..      **.   .    ....      .   **  *.. . *      .... .       . ..    .. .*   *     *.       9
33  8.0 - 16.0 V   . .. . .. .   ..     *.     .    ....      .        .. .        .... .       . ..    .. .           .       1
34 10.0 - 16.0 V   . .. . .. .   ..     *.     .    ....      .        .. .        .... .       . ..    ..*.           .       2
35  1.0 -  2.0 V   . ..*. .. .   ..        .   .    ....      .        .. .        .... .       . ..    .. .           .       1
36  2.0 -  3.0 V  *. .. . .. .   ..*       .   .    .... **   .        .. .        .... .       . ..    .. .  *        .       5
37  1.0 -  3.0 H   . ..*. .. .   ..        .   .    ....      .        .. .        .... .       . ..    .. .           .       1
38  1.5 -  3.5 H   . .. . .. .   ..        .   .    ....  *  *.        .. .        .... .     *  . ..    .. .  *        .       4
39  2.0 -  4.0 H  *. .. . .. .   ..*       .   .    .... **   .        .. .        .... .     *  . ..    .. .  *        .       6
40  2.5 -  4.5 H   . .. . .. .   ..*       .   .    ....  * * .        .. .        .... .     *  . ..    .. .  *        .       5
41  3.0 -  5.0 H   . .. . .. .   ..        .   .    ....      .        .. .        .... .    **  . ..    .. .   *       .       3
42  3.5 -  5.5 H   . .. . .. .   ..*       .   . *  ....      .       **.. .     *  .... .       . ..    .. .** *     * .*    10
43  5.0 -  7.0 H   . .. . .. .   ..        .   .*   ....      .       * .. .     *  .... .       . ..    .. .      *    .*     5
44  6.5 -  8.5 H   . .. . .. .   ..   *    .   .    ....      .        *.. .        .... .  *    . ..    .. .*          .*     5
45  8.0 - 16.0 H   . .. . .. .   ..        .   .    ....      .       **.. .        .... .       . ..    .. .           .       2
46 10.0 - 16.0 H   . .. . .. .   ..        .   .    ....      .        .. .        .... .       . ..    .. .           .       0
47  1.0 -  2.0 H   . ..*. .. .   ..        .   .    ....      .        .. .        .... .       . ..    .. .           .       1
48  2.0 -  3.0 H   . .. . .. .   ..        .   .    .... **  *.        .. .        .... .       . ..    .. .  *        .       4
```

Table VII.6.3 b) This table shows the 'valid' detections for all Pg phases in the data base.

```
                                                              Event number

                          10        20        30        40        50        60        70        80        90       100     #valid
No.  Beam type             !         !         !         !         !         !         !         !         !         !     entries

 1  1.0 -  3.0 P              ... ..       ..              .       .   ...        .       . .      .    .       .  .      0
 2  1.5 -  3.5 P              ... ..       ..              .       .   ...        .       . .      .    .       .  .      0
 3  2.0 -  4.0 P              ... ..       ..              .       .   ...        .       . .      .    .       .  .      0
 4  2.5 -  4.5 P              ... ..       ..              .       .   ...        .       . .      .    .       .  .      0
 5  3.0 -  5.0 P              ... ..       ..              .       .   ...        .*      . .      .    .       .  .      1
 6  3.5 -  5.5 P              ... ..       ..              .       .   ...        .*      . .      .    .       .  .      1
 7  5.0 -  7.0 P              ... ..       ..              .       .   ...        .*      . .      .    .       .  .      1
 8  6.5 -  8.5 P              ... ..       ..              .       .   ...        .*      . .      .    .       .  .      1
 9  8.0 - 16.0 P              ... ..       ..              .       .   ...        .*      . .      .    .       .  .      1
10 10.0 - 16.0 P              ... ..       ..              .       .   ...        .*      . .      .    .       .  .      1
11  1.0 -  2.0 P              ... ..       ..              .       .   ...        .       . .      .    .       .  .      0
12  2.0 -  3.0 P              ... ..       ..              .       .   ...        .       . .      .    .       .  .      0
13  1.0 -  3.0 S              ... ..       ..              .       .   ...        .       . .      .    .       .  .      0
14  1.5 -  3.5 S   *          ...*..       ..              .       .   ...        .       . .   *  .    .       .  .      3
15  2.0 -  4.0 S   * *        ...*..       ..        *     .       . * ...        .       . .   *  .    .       .  .      6
16  2.5 -  4.5 S     *       *...*..       ..        *     .       . * ...        .       . .      .    .       .  .      5
17  3.0 -  5.0 S              ... ..       ..              .       .   ...        .       . .      .    .       .  .      0
18  3.5 -  5.5 S              ... ..       ..              .       .   ...        .       . .      .    .       .  .      0
19  5.0 -  7.0 S              ... ..       ..              .       .   ...        .       . .      .    .     * .  .      1
20  6.5 -  8.5 S              ... ..       ..              .       .   ...        .       . .      .    .       .  .      0
21  8.0 - 16.0 S              ... ..       ..              .       .   ...        .       . .      .    .       .  .      0
22 10.0 - 16.0 S              ... ..       ..              .       .   ...        .       . .      .    .       .  .      0
23  1.0 -  2.0 S              ... ..       ..              .       .   ...        .       . .      .    .       .  .      0
24  2.0 -  3.0 S              ... ..       ..              .       .   ...        .       . .      .    .       .  .      0
25  1.0 -  3.0 V              ... ..       ..              .       .   ...        .       . .   *  .    .       .  .      1
26  1.5 -  3.5 V              ... ..       ..              .       .   ...        .  *    . .   *  .    .       .  .      2
27  2.0 -  4.0 V     *        ...*..       ..              .       .   ...        .       . .   *  .    .       .  .      3
28  2.5 -  4.5 V     *        ...*..       ..              .       .   ...        .  *    . .   *  .    .       .  .      4
29  3.0 -  5.0 V              ... ..       ..              .       .   ...        .  *    . .      .    .       .  .      1
30  3.5 -  5.5 V              ... ..       ..              .       .   ...        .       . .      .    .       .  .      0
31  5.0 -  7.0 V              ... ..       ..              .       .   ...        .*      . .      .    .       .  .      1
32  6.5 -  8.5 V              ... ..       ..              .       .   ...   *    .*      . .      .    .       .  .      2
33  8.0 - 16.0 V              ... ..       ..              .       .   ...   *    .*      . .      .    .       .  .      2
34 10.0 - 16.0 V              ... ..       ..              .       .   ...   *    .*      . .      .    .       .  .      2
35  1.0 -  2.0 V              ... ..       ..              .       .   ...        .       . .      .    .       .  .      0
36  2.0 -  3.0 V   * *        ...*..       ..              .       .   ...        .       . .   *  .    .       .  .      4
37  1.0 -  3.0 H              ... ..       ..              .       . * ...        . **    . .* *   .    .       .  .      5
38  1.5 -  3.5 H              ... ..       ..              .     * . * ...        .  *   *. .* *   .    .       .  .      6
39  2.0 -  4.0 H   * *        ...*..       ..              .     * . * ...        .  *   *. .* *   .    .       .  .      9
40  2.5 -  4.5 H   * *       *...*..       ..        *     .     * . * ...        .    * *. .* *   .    .   *   .  .     12
41  3.0 -  5.0 H   * *       *... ..       ..    *   *     .     **. * ...        .  **  *. .* *   .    .   *   .  .     14
42  3.5 -  5.5 H   ***     ***... ..       ..    *  ****   .     **. * ...*    *  .  ** * . .*     .    .   *   .  .*     22
43  5.0 -  7.0 H   **** * ****...*..       ..    ** **** * .   *** . **...* *  *  .   * * . .  *   .    .** *   .  .**     33
44  6.5 -  8.5 H   ** *** ****...*..       .. *  ** ****** .* **** . **...*   **  .     * .*.    **.* * .** *  *. *.* *    42
45  8.0 - 16.0 H  *** ********...*..*******.. *************.****** .***...**  *  *.   *** .*. *  **.*** .***** *.**.* *    65
46 10.0 - 16.0 H  *** ********...*..*******..* ****** *****.****** .***...**  * **.   *** .*. *  **.****.***** *.**.* *    66
47  1.0 -  2.0 H              ... ..       ..              .       .   ...        . *     . .  *   .    .       .  .      2
48  2.0 -  3.0 H     *        ...*..       ..              .       . * ...        .       . .* *   .    .       .  .      5
```

Table VII.6.3 c) This table shows the 'valid' detections for all Sn phases in the data base.

```
                                                               Event number

                            10        20        30        40        50        60        70        80        90       100     #valid
No.   Beam type              !         !         !         !         !         !         !         !         !         !    entries

  1  1.0 -  3.0  P     .     ..    .                  ...       .                           .     .    ..  .          .         0
  2  1.5 -  3.5  P     .     ..    .                  ...       .                 *  *      .     .    ..  .          .         2
  3  2.0 -  4.0  P  *  .*    .. *  . *   * *   *  *   ...   ** *.              *  *  *    * . * * .    .. *.**     *  .        21
  4  2.5 -  4.5  P     .     ..    .*                 ...   *  *. *              *  *       . * * .    ..  . *      * .        10
  5  3.0 -  5.0  P   * .    *..    .*   *             ...*  **  .***    *          *      * .    *.    ..  . * **   * .        18
  6  3.5 -  5.5  P   **.    *..    .    *  *   * ** * ...*  **  .*** ** *   **      *    * * .   **. *  .. *. * ***  **. *      34
  7  5.0 -  7.0  P   * .     ..    .                  ...       .           **                  .     .    ..  .          .         3
  8  6.5 -  8.5  P     .     ..    .                  ...       .                           .     .    ..  .          .         0
  9  8.0 - 16.0  P     .     ..    .                  ...       . * *                       .     .    ..  .          .         2
 10 10.0 - 16.0  P     .     ..    .  *               ...       .     *                     .     .    ..  .          .         2
 11  1.0 -  2.0  P     .     ..    .                  ...       .                           .     .    ..  .          .         0
 12  2.0 -  3.0  P     .     ..    .                  ...       .                           .     .    ..  .          .         0
 13  1.0 -  3.0  S     .*    ..    .     *            ...       .                           .*  * .    ..  .          .         4
 14  1.5 -  3.5  S  *  .     .. *  .*     **  ** *    ...     * .          *      *   *     . * * .**  ..**.          .        18
 15  2.0 -  4.0  S  * *.    *.. *  .**   *** **** *  *...*    * .*    *  * *** *  *    *    . * * .**  ..**.     * *  .*       35
 16  2.5 -  4.5  S   **.    *.. *  .**  ** * **** *  *...    * *.** *** ** * * **   **  *** * . ****. *  ..**.    ****** .**      48
 17  3.0 -  5.0  S   * .     ..    .**  ** * **   *  *...   ** *.** *** *          *** ** **. ****.    ..**. * ** *** . *      39
 18  3.5 -  5.5  S   * .    *..    .**  ** ** *   *   ...   ** *.** *** * * *  *      *   *****. ****.    ..**. * ** *** . *      40
 19  5.0 -  7.0  S     .    *..    .                  ...       .     *    **      *  *     .  *  .    ..  .          .         7
 20  6.5 -  8.5  S     .     ..    .                  ...       . *  *  * *  **    **       * .  *  .    ..  .      * .        11
 21  8.0 - 16.0  S     .     ..    .                  ...       . * **    *                 .     .    ..  .      * .         5
 22 10.0 - 16.0  S     .     ..    .  *               ...       . *                         .     .    ..  .          .         2
 23  1.0 -  2.0  S     .     ..    .                  ...       .                           .     .    ..  .          .         0
 24  2.0 -  3.0  S     .     ..    .                  ...       .                           .     .    ..  .          .         0
 25  1.0 -  3.0  V  *  .*    ..****.   * **   ***     ...    ***. **   *   *         ***    .* ** .* **..* .          .*        30
 26  1.5 -  3.5  V  *  .*    .. ***.*   ****  *** *  *...   ****.* *   *   *      *  **    * .* ***.*** ..**. **    *  .*       40
 27  2.0 -  4.0  V  * *.*   *..   *.*   ***** *** *  *...*  ****.*         **   * *  ***  * .*****.**  ..**. * * *  .**      45
 28  2.5 -  4.5  V   * .*   *..    .*   ** ****** *  *...*  ****.**  ** *         *    *  * * . ****.**  ..**.** * * *  .**      43
 29  3.0 -  5.0  V   * .    *..    .*   ** ** **  *   ...*  *  *.**  ** *              *  * * . ****. *  .. *.** *** ***. *      36
 30  3.5 -  5.5  V   * .    *..    .*   ** *  *   *   ...   ** *.****** *   **     *   *****. ****.    .. *.** *** ***. *      40
 31  5.0 -  7.0  V   * .     ..    .    *       * *   ...   *   . **  * *   ***    *      * .  ** . *  ..  .** *    **. *      22
 32  6.5 -  8.5  V     .     ..    .                  ...       . ** *  * * **     *      * .     .    .. *.      * .        11
 33  8.0 - 16.0  V     .     ..    .                  ...       .       *                   .     .    ..  .      * .         2
 34 10.0 - 16.0  V     .     ..    .  *               ...       .                           .     .    ..  .          .         1
 35  1.0 -  2.0  V  *  .** * ..** *.     **   * *  ** ... ***   . **   *         *    *     .*  * . **..  . *        .        26
 36  2.0 -  3.0  V     .*    .. *  .*   ****  *** *   ...   *** .  *       **   *    ***    .* ** .*** ..**. **  *    .*       33
 37  1.0 -  3.0  H     .*    .. ** .     *            ...  ***  . **   **         **  *     .** * .* **.. *. *        .*       23
 38  1.5 -  3.5  H    *.     .. ** .    ** *   *  *   ...   **  . **    *         *  *     .** * .****.. *. **    *  .**      28
 39  2.0 -  4.0  H    *.    *..  * . *  ** *   *  *   ...    *  .                     *    **.   * .** *.. *.* **   *  .**      24
 40  2.5 -  4.5  H    *.    *..    .**  ** *   * **  *...   **  .*    *      * *     *    **. *   .**  .. *.**** * *  .**      32
 41  3.0 -  5.0  H   **.* * *..    .** *** * * * **  *...    * *.*    *     ** *   * *    **. *   .**  .. *.* **** *  . *      38
 42  3.5 -  5.5  H  ** .* * *..    .** *** * * * **  *...   ** *.*** ** *   ** **  * *    **. *  *.**  .. *.********. *      49
 43  5.0 -  7.0  H   * .     ..    .    ** * *   **  *...       . *  ** *    * *            * . * * .    .. *.   *** *  . *      23
 44  6.5 -  8.5  H     .     ..    .    ** * * *  *  *...       . *  ** * *  **    **    ** * . * * .    .. *.         * . *      23
 45  8.0 - 16.0  H     .     ..    .       * *    *   ...       . * *** * * * *    **    ** * .   * .    .. *.          .        17
 46 10.0 - 16.0  H     .     ..    .         *        ...       . * ***   * *       *      * .     .    ..  .          .         9
 47  1.0 -  2.0  H  *  .*  * .. ** .          *       ...  * *  . **   **         *     *     .*  * . **..  .          .*        19
 48  2.0 -  3.0  H     .     .. ** .    **        *   ...   **  .                           .*  * .** *.. *. *     *  .**      17
```

Table VII.6.3 d) This table shows the 'valid' detections for all Lg phases in the data base.

a)

Beam 10	10.0 - 16.0 P	60 entries	
Beam 6	3.5 - 5.5 P	22 entries	
Beam 7	5.0 - 7.0 P	5 entries	96%
Beam 9	8.0 - 16.0 P	4 entries	
Beam 22	10.0 - 16.0 V	3 entries	

Beam 4	2.5 - 4.5 P	2 entries	
Beam 5	3.0 - 5.0 P	1 entry	4%
Beam 27	2.0 - 4.0 V	1 entry	

Total number of detected Pn-phases : 98

b)

Beam 6	3.5 - 5.5 P	38 entries	
Beam 4	2.5 - 4.5 P	8 entries	
Beam 16	2.5 - 4.5 S	6 entries	
Beam 8	6.5 - 8.5 P	4 entries	
Beam 31	5.0 - 7.0 V	4 entries	97%
Beam 13	1.0 - 3.0 S	3 entries	
Beam 25	1.5 - 3.5 V	3 entries	
Beam 18	2.5 - 5.5 S	2 entries	

Beam 3	2.0 - 4.0 P	1 entry	3%
Beam 20	6.5 - 8.5 V	1 entry	

Total number of detected Pg-phases : 70

c)

Beam 46	10.0 - 16.0 H	66 entries	
Beam 41	3.5 - 5.5 H	7 entries	
Beam 43	5.0 - 7.0 H	3 entries	96%
Beam 32	6.5 - 8.5 V	2 entries	
Beam 14	1.5 - 3.5 S	1 entry	

Beam 19	5.0 - 7.0 S	1 entry	
Beam 37	1.0 - 3.0 H	1 entry	4%
Beam 44	6.5 - 8.5 H	1 entry	

Total number of detected Sn-phases : 82

d)

Beam 42	3.5 - 5.5 H	49 entries	
Beam 25	1.0 - 3.0 V	19 entries	
Beam 35	1.0 - 2.0 V	7 entries	96%
Beam 16	2.5 - 4.5 S	6 entries	
Beam 27	2.0 - 4.0 V	3 entries	

Beam 20	6.5 - 8.5 S	2 entries	4%
Beam 37	10.0 - 16.0 P	1 entry	

Total number of detected Lg-phases : 87

Table VII.6.4 (a-d) In these tables we give the beam priority lists for detection of Pn, Pg, Sn and Lg phases that result from applying the iterative procedure to each phase type individually.

			Number of traces to be filtered	Number of beams to be formed
Beam 46	10.0 - 16.0 H	:	8	1
Beam 10	10.0 - 16.0 P	:	4	4
Beam 42	3.5 - 5.5 H	:	8	1
Beam 6	3.5 - 5.5 P	:	4	4
Beam 41	3.5 - 5.5 H	:	8	1
Beam 35	1.0 - 2.0 V	:	17	1
Beam 16	2.5 - 4.5 S	:	6	6
Beam 7	5.0 - 7.0 P	:	4	4
Beam 9	8.0 - 16.0 P	:	4	4
Beam 8	6.5 - 8.5 P	:	4	4
Beam 31	5.0 - 7.0 V	:	22	1
Beam 22	10.0 - 16.0 V	:	22	1
Beam 13	1.0 - 3.0 S	:	6	6
Beam 25	1.5 - 3.5 V	:	17	1
Beam 43	5.0 - 7.0 H	:	8	1
Beam 18	2.5 - 5.5 S	:	6	6
Beam 32	6.5 - 8.5 V	:	22	1
Beam 14	1.5 - 3.5 S	:	8	8
			178	55
Symmetric deployment		:	222	99

Table VII.6.5 From the results produced by the iterative procedure with each phase type treated individually, the beam deployment given in this table was inferred. For each phase type, this beam deployment cover 96% of the 'valid' detections. We have also given the number of traces to be filtered and the number of beams to be formed. To cover the North Sea / western Norway region 178 traces must be filtered and 55 beams formed. To span all azimuth directions by the coherent beam deployment the numbers will be 222 and 99, respectively. Note that for incoherent beamforming, each individual trace must be filtered prior to the beamforming.

			Number of traces to be filtered	Number of beams to be formed
Beam 46	10.0 - 16.0 H	:	8	1
Beam 10	10.0 - 16.0 P	:	4	4
Beam 42	3.5 - 5.5 H	:	8	1
Beam 6	3.5 - 5.5 P	:	4	4
Beam 25	1.0 - 3.0 V	:	17	1
Beam 4	2.5 - 4.5 P	:	4	4
Beam 8	6.5 - 8.5 P	:	4	4
Beam 39	2.0 - 4.0 H	:	8	1
Beam 35	1.0 - 2.0 V	:	17	1
Beam 18	3.5 - 5.5 S	:	6	6
Beam 31	5.0 - 7.0 V	:	22	1
Beam 22	10.0 - 16.0 V	:	22	1
Beam 7	5.0 - 7.0 P	:	4	4
			128	33
Symmetric deployment		:	154	59

Table VII.6.6 The beam deployment of this table was produced by the iterative procedure when treating all phases at the same time, after first having required that beam nos. 46, 10, 42 and 6 should be included in the final deployment. Compared to the results presented in Table VII.6.5, the volume of the beam deployment is considerably reduced.

		Number of traces to be filtered	Number of beams to be formed
Beam 46	10.0 - 16.0 H	8	1
Beam 10	10.0 - 16.0 P	4	4
Beam 42	3.5 - 5.5 H	8	1
Beam 6	3.5 - 5.5 P	4	4
Beam 25	1.0 - 3.0 V	17	1
Beam 4	2.5 - 4.5 P	4	4
Beam 8	6.5 - 8.5 P	4	4
Beam 39	2.0 - 4.0 H	8	1
Beam 35	1.0 - 2.0 V	17	1
Beam 31	5.0 - 7.0 V	22	1
Beam 22	10.0 - 16.0 V	22	1
Beam 7	5.0 - 7.0 P	4	4
Beam 9	8.0 - 16.0 P	4	4
Beam 29	3.0 - 5.0 V	22	1
		148	32
Symmetric deployment		172	56

Table VII.6.7 The procedure for finding the results given in this table, is essentially the same as outlined for Table VII.6.6. The only difference is that we have not allowed any S-beams to be included in the final beam deployment.

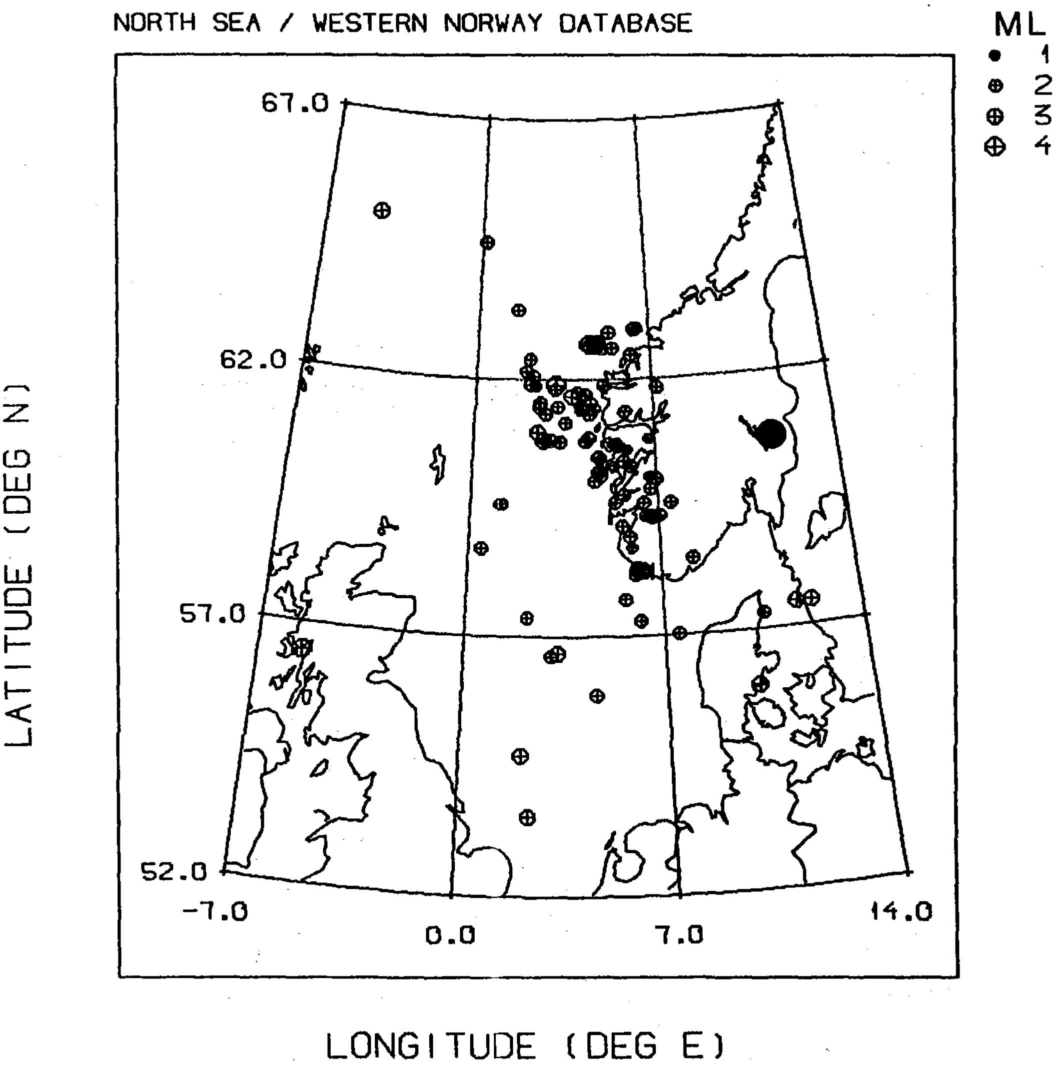

Fig. VII.6.1 The figure shows the locations of the 101 events in the North Sea / western Norway data base. The loaction of the NORESS array is indicated by a filled circle.

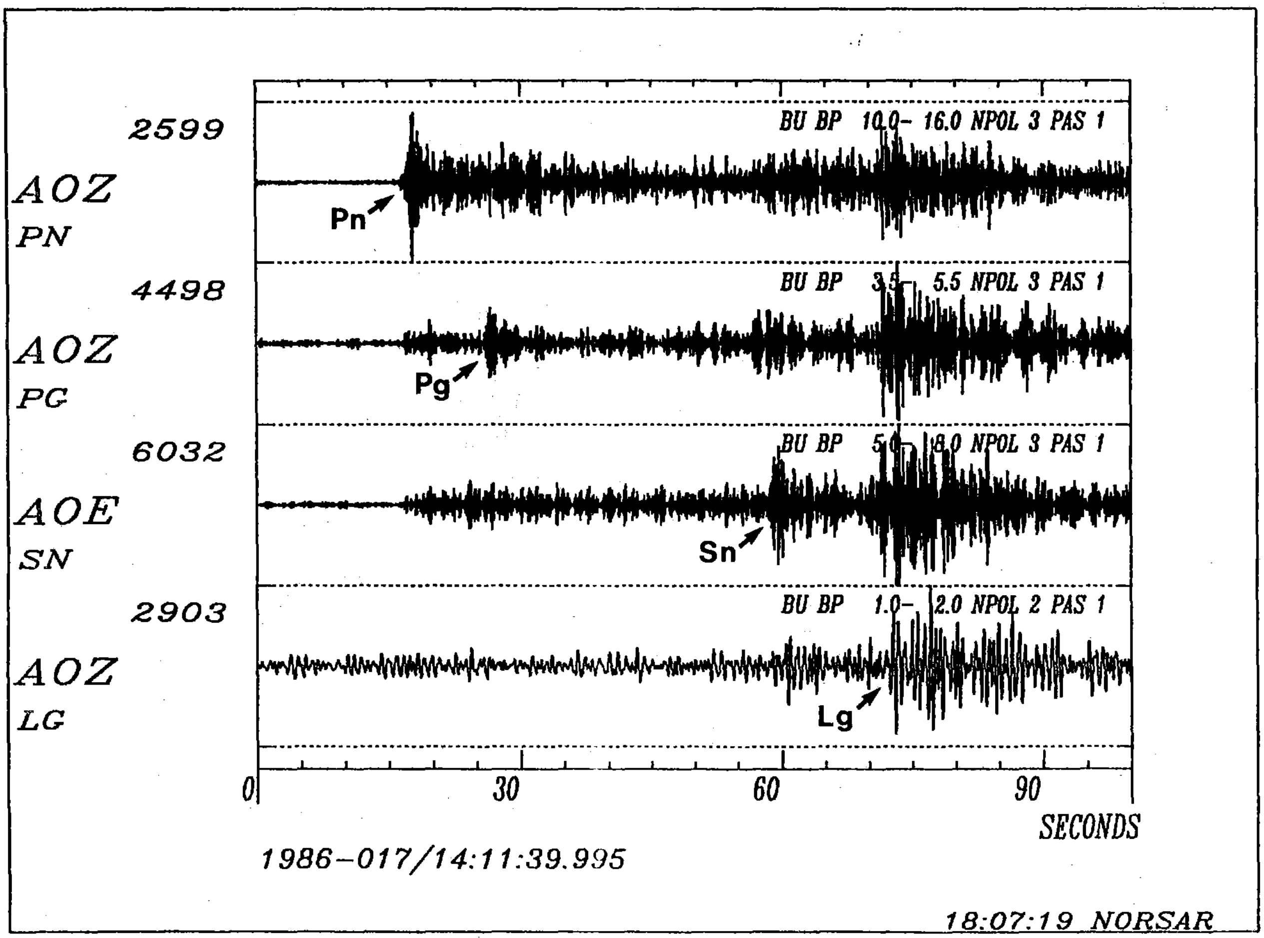

Fig. VII.6.2 To identify the different regional phases and pick their arrival times, several filters were applied to both the vertical and horizontal components. This figure shows filtered NORESS recordings from an event in southwestern Norway. The distance from NORESS is about 400 km and the local magnitude is 2.7.