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6.1 Experimental inclusion of the Eskdalemuir array in the automatic regional array processing system at NORSAR

6.1.1 Introduction

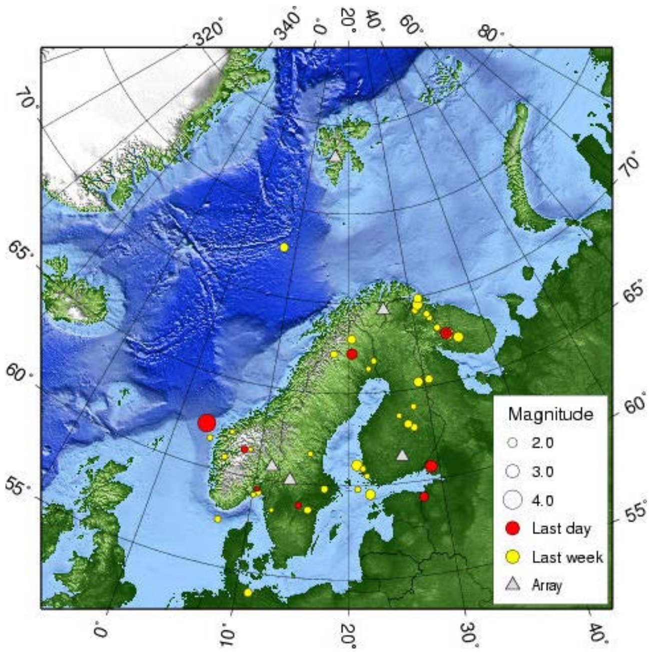
NORSAR has since 1991 carried out processing and analysis of seismic events in the European Arctic, using the regional array network in Fennoscandia and NW Russia. In previous Semiannual Technical Summaries, we have described the basic algorithms as well as a number of enhancements made to the regional processing at NORSAR over the years; see for example Kværna et al. (1999), Ringdal and Kværna (2004) and Schweitzer and Kværna (2006).

In summary, the regional processing comprises the following steps:

- Automatic single array processing, using a suite of bandpass filters in parallel and a beam deployment that covers both P and S type phases for the region of interest.
- An STA/LTA detector applied independently to each beam, with broadband f-k analysis for each detected phase in order to estimate azimuth and phase velocity.
- Single-array phase association for initial location of seismic events, and also for the purpose of chaining together phases belonging to the same event, so as to prepare for the subsequent multi-array processing.
- Multi-array event detection, using the Generalized Beamforming (GBF) approach (Ringdal and Kværna, 1989) to associate phases from all stations in the regional network and thereby provide automatic network location estimates for detected events in all of northern Europe. The resulting automatic event list is made available on the Internet (www.norsardata.no).
- Interactive analysis of selected events, resulting in a reviewed regional seismic bulletin, which includes hypocentral information, magnitudes and selected waveform plots. This reviewed bulletin is also available on the Internet.

The stations contributing to the automatic processing currently include the Fennoscandian seismic arrays (NORES, ARCES, NOA, HFS, FINES) as well as the Spitsbergen and Apatity arrays. A typical example of the automatic processing results as provided on Internet is shown in Figure 6.1.1. In our subsequent interactive analysis we also make use of some of the three-component seismic stations in the region to improve the event location accuracy.

Experience over the past several years has demonstrated that the automated event list generated by the GBF procedure is nearly "complete", in the sense that it provides close to an exhaustive search of all possible phase combinations that could correspond to real events. The reviewed bulletin is much more selective, since our available resources allow a complete analysis of only a small subset of the seismic event candidates that are associated through the automatic algorithms. An important topic of current research is to develop methods to enable the analyst to easily select events from areas of particular interest, and focus on these events in the interactive analysis.



Origin time	Lat	Lon	Azres	Timres	Nph	Nst	Mag	Area
2014-290:08.08.10	60.71	29.14	4.91	1.71	6	3	2.53	BALTIC STATES-BELARUS-NW RUSSIA REGION
2014-290:03.39.47	67.70	34.31	6.18	2.29	4	2	1.12	BALTIC STATES-BELARUS-NW RUSSIA REGION
2014-289:22.43.46	62.27	3.33	6.77	2.85	13	7	3.73	MOERE SHELF
2014-289:17.03.08	67.19	20.49	6.34	1.51	7	6	2.18	CENTRAL NORBOTTEN SWEDEN
2014-289:16.52.57	61.39	8.23	8.17	2.11	5	3	1.40	OPPLAND-HEDMARK NORWAY
2014-289:13.00.40	58.83	14.85	10.53	2.53	4	3	1.50	EASTERN GOETALAND SWEDEN
2014-289:11.50.20	67.68	34.30	5.78	1.56	5	2	2.45	BALTIC STATES-BELARUS-NW RUSSIA REGION
2014-289:11.31.34	59.14	27.86	8.59	2.93	4	2	1.93	BALTIC STATES-BELARUS-NW RUSSIA REGION
2014-289:11.01.24	59.43	10.37	5.97	0.59	6	4	1.03	OSLO REGION NORWAY
2014-288:23.51.16	67.99	20.45	6.95	1.18	4	2	1.80	CENTRAL NORBOTTEN SWEDEN
2014-288:21.59.52	66.35	22.76	10.78	2.93	4	3	1.14	SWEDISH-FINISH BORDER ZONE
2014-288:15.53.40	61.57	4.16	12.47	2.96	5	3	1.28	NORTHERN NORTH SEA
2014-288:14.54.13	69.90	31.27	13.46	2.53	4	2	1.89	NORWAY-MURMANSK BORDER REGION
2014-288:14.17.50	58.42	12.17	4.22	1.66	6	3	1.02	VAERMLAND REGION SWEDEN
2014-288:13.17.17	57.45	7.06	11.28	3.17	8	3	1.49	EASTERN NORTH SEA
2014-288:11.05.14	68.10	33.26	3.05	0.85	4	3	1.47	BALTIC STATES-BELARUS-NW RUSSIA REGION
2014-288:11.02.23	59.79	17.43	7.05	1.52	10	4	1.63	VAESTMANLAND REGION SWEDEN
2014-288:10.01.23	65.40	30.60	5.77	3.79	6	4	1.79	FINLAND-KARELIA BORDER REGION
2014-288:09.50.49	67.29	35.86	6.51	1.05	4	3	2.20	BALTIC STATES-BELARUS-NW RUSSIA REGION
2014-288:08.04.24	62.18	6.43	5.97	1.06	5	3	1.03	SOGN-MOERE REGION NORWAY
2014-288:07.29.08	60.78	6.25	3.57	0.79	5	3	1.28	HARDANGER NORWAY
2014-288:03.35.24	67.70	34.31	8.80	2.25	4	3	1.70	BALTIC STATES-BELARUS-NW RUSSIA REGION
2014-288:02.43.35	67.70	34.83	9.71	2.29	6	2	1.52	BALTIC STATES-BELARUS-NW RUSSIA REGION
2014-288:00.24.27	69.57	31.02	5.09	1.14	4	3	2.13	NORWAY-MURMANSK BORDER REGION

Fig. 6.1.1 Example of the NORSAR on-line automatic GBF processing results that are made available on the Web. These solutions are not reviewed by an analyst, and should therefore be interpreted with caution. The network of seismic arrays used in this processing is marked by triangles.

6.1.2 Monitoring North Sea seismicity

One of the primary areas of interest for the regional processing at NORSAR is the North Sea region. The seismicity pattern of this region is well known, and it is illustrated in Figure 6.1.2, based on the ISC bulletin for the time period 2000 – 2014. We show the seismicity with three different magnitude constraints (M>2.5, M>3.0 and M>3.5) in order to minimize any possible bias due to geographical variations in the regional event detection capability.

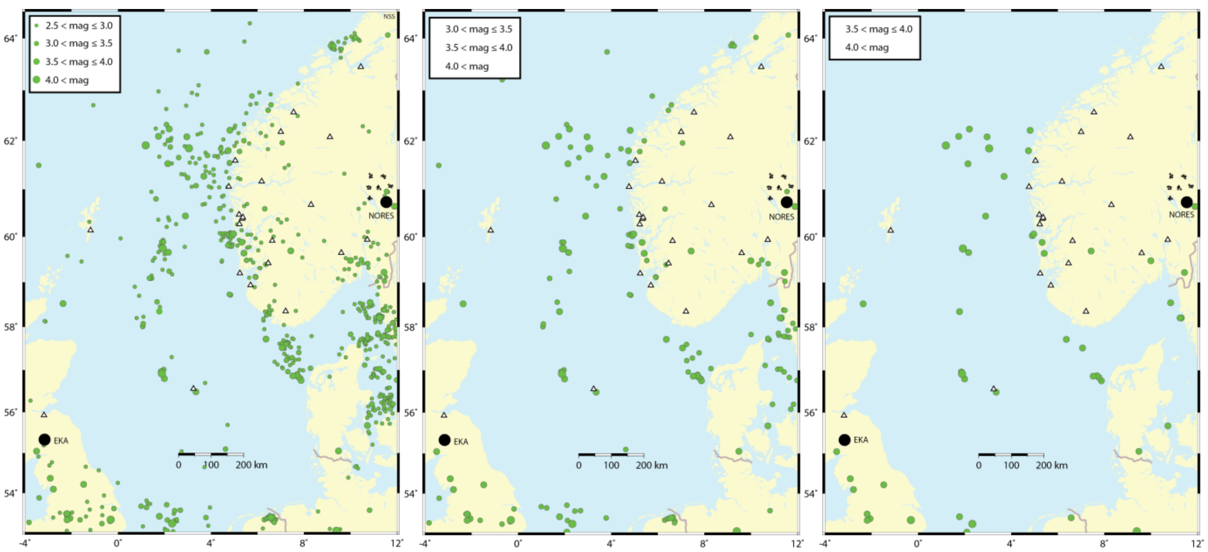


Fig. 6.1.2 Seismicity of the North Sea area as given in the ISC bulletin for the time period 2000 - 2014. The map shows all reported events with magnitude M restricted to a) M> 2.5, b) M>3.0 and c) M>3.5. The location of the two seismic arrays NORES (NRS) and EKA are labelled, and the stations of the Norwegian National Seismic Network (NNSN) are shown by black triangles.

From Figure 6.1.2 we can conclude that the seismic activity is not homogeneous in the general North Sea area. Most of the earthquakes occur near the west coast of Norway, with much lower seismic activity in the area near Britain. Some of the smaller events are likely explosions, but we are confident that all the events above M=3.5 are earthquakes. We are also confident that all seismic events above 3.5 in the region have been detected and included in the ISC bulletin.

An issue that must be considered with regard to NORSAR's regional monitoring of the North Sea is the location of the regional array network currently contributing to our processing. As can be seen from Figure 6.1.1, this network has a very poor azimuthal coverage of the North Sea region. A seismic array that might contribute to an improved coverage in this regard is the Eskdalemuir array (EKA) in Scotland, the location of which is indicated on Figure 6.1.2. The EKA array geometry is shown in Figure 6.1.3. The array is composed of two arms approximately at right angles, each arm being about 8 km long with seismometers at intervals of about 1 km. EKA has been in operation for more than 40 years, and has been designated as an auxiliary seismic station in the International Monitoring System for the Comprehensive Nuclear-Test-Ban Treaty. The excellent teleseismic detection capabilities of the array have been well documented over the years, and in addition, as we will document in this paper, the array is well suited for monitoring regional seismicity.

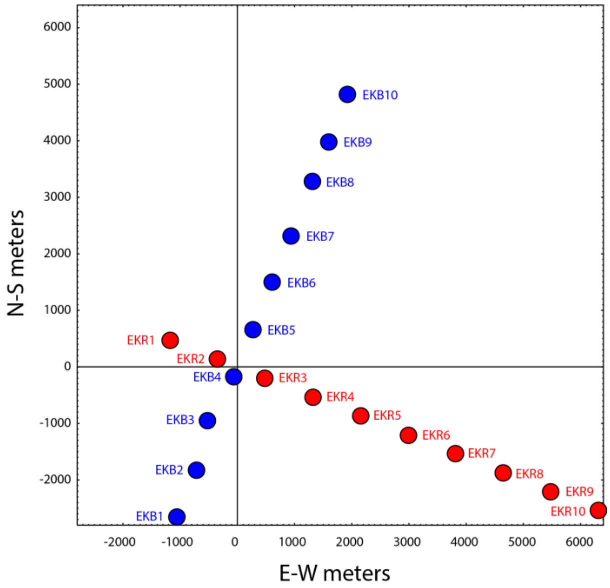


Fig. 6.1.3 Geometry of the Eskdalemuir seismic array (EKA) in Scotland.

6.1.3 Testing the NORSAR GBF with the inclusion of EKA array data

NORSAR has access to real-time EKA data, but until now these data have not been used in our automatic GBF analysis. In this paper we investigate the potential improvements obtained by including the EKA array in the automatic regional processing system, especially in connection with the monitoring of low-magnitude seismicity in the North Sea.

We have run experimental GBF network processing with inclusion of the EKA array since 1 December 2013, covering a period of approximately 10 months. This has been done in parallel to our regular GBF processing and has resulted in a comprehensive joint automatic seismic bulletin. An example of the result of this automatic processing for an event in the North Sea is shown in Figure 6.1.4.

EASTERN NORTH SEA

Origin time	Lat	Lon	Azres	Timres	Wres	Nphase	Ntot	Nsta	Netmag
2014-084:18.19.55.0	57.09	7.28	8.04	3.21	5.22	8	14	4	1.65

Sta	Dist	Az	Ph	Time	Tres	Azim	Ares	Vel	Snr	Amp	Freq	Fkq	Pol	Arid	Mag
NRS	474.6	213.0	Pn	18.21.01.5	0.7	208.9	-4.1	7.9	13.9	455.1	12.25	2		258383	
NRS	474.6	213.0	p	18.21.09.4		206.8	-6.2	9.5	8.7	191.7	4.18	1		258386	
NRS	474.6	213.0	Sn	18.21.51.3	2.3	193.1	-19.9	4.3	8.1	736.6	8.01	2	-3	258390	1.43
HFS	504.5	230.5	Pn	18.21.05.0	0.6	229.4	-1.1	8.2	5.8	312.2	8.00	2	-1	258384	
HFS	504.5	230.5	p	18.21.11.8		227.2	-3.3	7.8	4.3	108.0	4.00	1		258385	
HFS	504.5	230.5	p	18.21.15.8		223.4	-7.1	7.1	2.6	141.0	10.00	3		258387	
HFS	504.5	230.5	p	18.21.19.3		228.8	-1.7	7.4	2.5	60.0	13.33	4		258388	
HFS	504.5	230.5	s	18.21.52.2		225.5	-5.0	4.9	3.5	269.5	5.71	3	3	258393	
HFS	504.5	230.5	Sn	18.21.58.1	2.9	235.0	4.5	4.6	4.5	252.0	4.11	3		258395	1.16
HFS	504.5	230.5	Lg	18.22.07.7	-11.4	238.4	7.9	3.8	2.7	280.4	4.28	3		258398	1.19
EKA	676.2	68.9	Pn	18.21.26.9	1.6	74.9	6.0	8.4	6.3	50.1	3.36	3	1	148300	
EKA	676.2	68.9	p	18.21.27.0		74.5	5.6	8.2	6.3	50.1	3.36	3	1	148295	
EKA	676.2	68.9	Sn	18.22.37.0	5.6	76.4	7.5	4.8	4.1	44.2	4.31	3	1	148305	2.32**
FIN	1172.2	254.0	Pn	18.22.26.2	0.7	240.7	-13.3	9.5	6.3	105.8	4.00	1	1	258392	

Fig. 6.1.4 Example showing the results from the automatic GBF processing including the EKA array for a low-magnitude seismic event in the Eastern North Sea. Note that we have not yet included an appropriate calibration factor for EKA magnitudes, which currently are too high.

We have analyzed in some detail the EKA data for the event shown in Figure 6.1.4 in order to obtain a closer impression of the array capability. Figure 6.1.5 illustrates the gain in signal-to-noise ratio (SNR) from beamforming on the EKA array. The plot displays the P-beam (red) and the S-beam (blue) together with the individual seismic channels (black). The traces are filtered in the 2-4 Hz band. We note a significant improvement in SNR both for the P-beam and the S-beam, which means that these phases would be easily detected by automatic processing.

Figure 6.1.6 shows frequency-wavenumber analysis of the same event. The cross-like patterns of the two plots reflect the geometry of the array, but we note that both plots have clear peaks that turn out to correspond well with the event location. The estimated phase velocities in the two plots correspond to a Pn phase and an Sn phase, respectively, and the estimated azimuths for the two phases are mutually consistent (74.9 and 74.2 degrees). Thus the results from EKA array processing are very satisfactory.

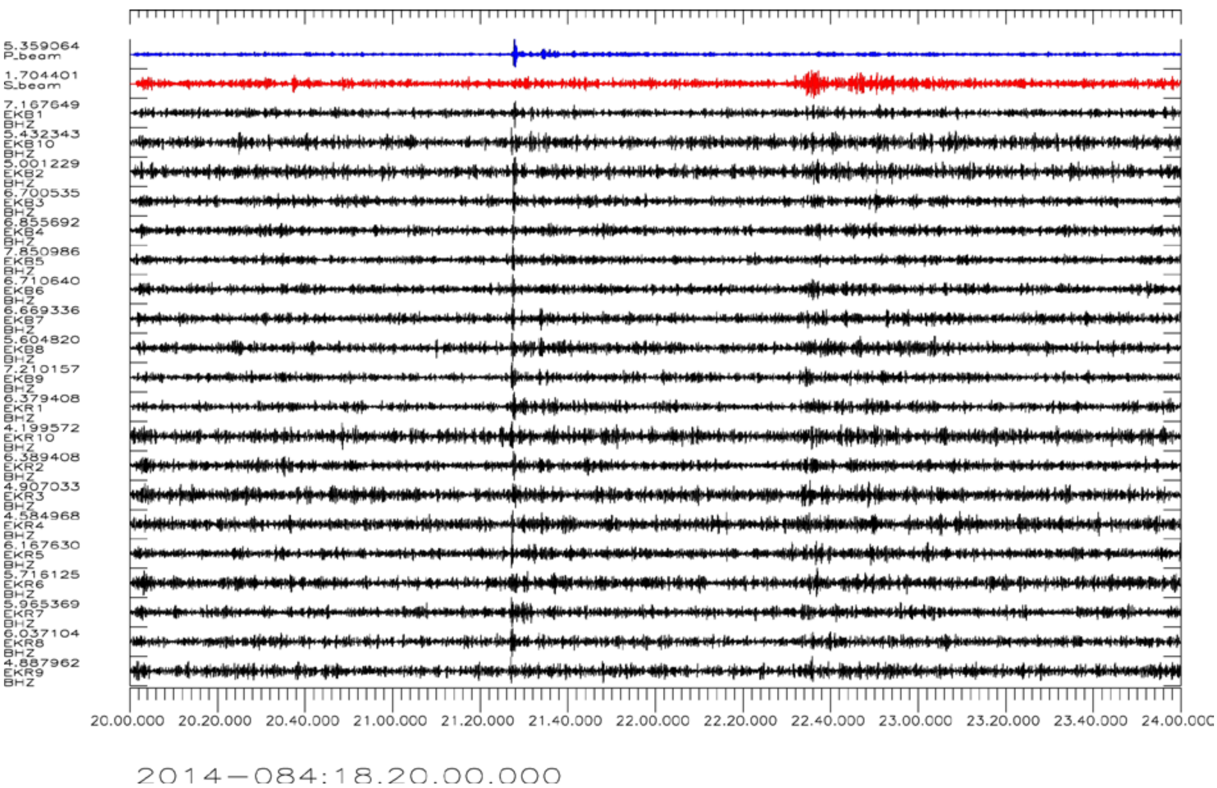


Fig. 6.1.5 Illustration of the gain in signal-to-noise ratio (SNR) from beamforming on the EKA array. The plot corresponds to the event shown in Figure 6.1.4, and displays the P-beam (red) and the S-beam (blue) together with the individual seismic channels (black). The traces are filtered in the 2-4 Hz band.

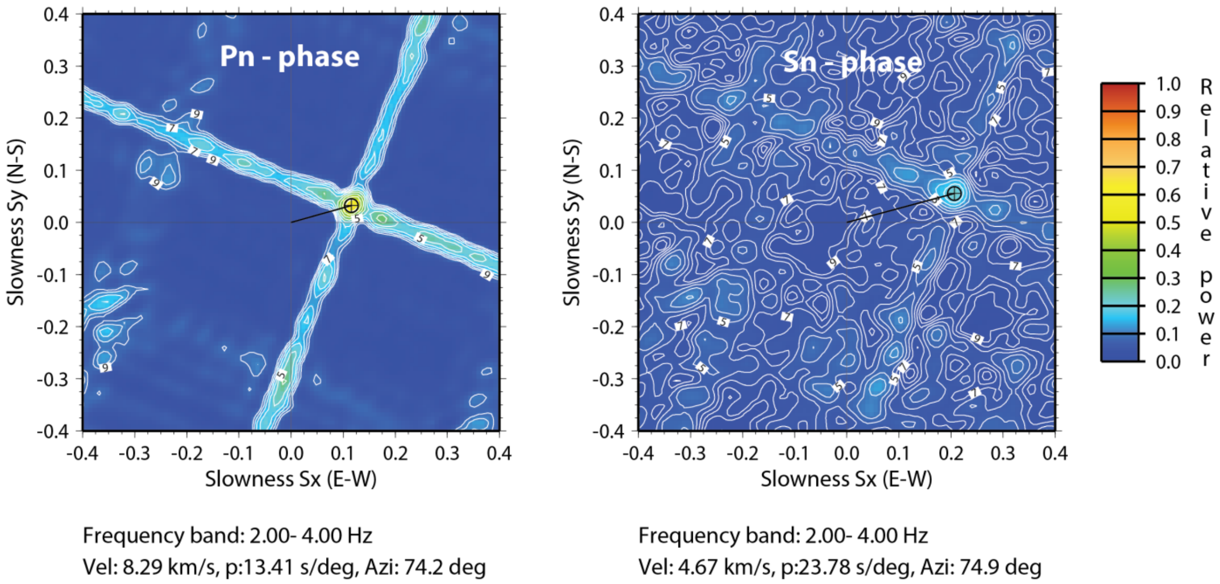


Fig. 6.1.6 Frequency-wavenumber analysis of the event shown in Figures 6.1.4 and 6.1.5. Note the excellent results for both the P-wave and S-wave, both with regard to phase velocity and azimuth.

Over the 10-month processing period with the EKA array, the GBF process has generated many thousand event candidates. Without analyzing the results in detail, we have noticed that a large number of acceptable events are within local distance from the array, and are detected and located by a standard EKA P and S phase combination. These local events are of little interest for our regional processing. Our primary interest is the possible improvements resulting from including EKA in our automatic monitoring of North Sea seismicity, and for the 10-month period we have compared the results of the two GBF processes (with or without EKA) for the general North Sea region (53°N-65°N, 5°W-10°E). Table 6.1.1 shows a subset of the processing results comprising those events in this region that fulfil the following criteria:

- At least two arrays with both a P-type and an S-type detection
- At least one P-type detection at the EKA array

These criteria are generally sufficient to ensure that the event is real, and the condition of at least one detected EKA P-phase would imply that the reliability of the event location would be improved because of the improved azimuthal coverage. We have reviewed all of the 40 events listed in Table 6.1.1, and found only two events (marked by X in the rightmost column) that are considered to be of questionable quality.

Table 6.1.1 List of selected seismic events in the North Sea general region during December 2013 through September 2014. The list comprise all events that fulfil the detection requirements specified in the text. The distance (km) from EKA and NORES (NRS) as well as the signal-to-noise ratio (SNR) at these two arrays are indicated for each event. Those events that have been included in the NORSAR reviewed regional bulletin are marked with N in the right hand column, whereas two events that have been determined to have a mis-associated phase and therefore are not considered acceptable are marked by X in that column.

	Origin time	Lat	Lon	Mag	Region	EKAdist	EKASNR	NRSdist	NRSSNR	
1	2013-335:08.13.58.0	57.05	7.06	2.02	EASTERN NORTH SEA	662.00	44.00	485.70	59.20	-
2	2013-335:09.48.17.0	60.63	1.80	2.88	VIKING GRABEN	659.00	348.50	532.40	1264.00	N
3	2013-339:14.26.47.0	58.44	6.10	1.61	ROGALAND NORWAY	661.80	4.80	399.70	41.60	-
4	2013-344:14.19.49.0	58.44	6.48	1.74	ROGALAND NORWAY	681.80	5.10	383.20	76.80	N
5	2013-344:21.07.17.0	56.90	7.84	2.68	EASTERN NORTH SEA	705.30	60.20	478.30	160.40	N
6	2013-354:14.18.26.0	58.64	5.90	1.68	ROGALAND NORWAY	662.30	4.00	394.20	33.70	N
7	2014-006:14.16.40.0	58.24	6.30	1.41	ROGALAND NORWAY	662.20	4.10	406.70	11.70	-
8	2014-014:14.19.12.0	58.24	6.68	1.15	AGDER NORWAY	682.60	3.50	391.20	10.60	-
9	2014-016:17.09.34.0	59.19	1.77	2.42	VIKING GRABEN	522.80	34.70	572.10	39.50	N
10	2014-021:06.39.03.0	61.02	5.09	2.46	SOGN-MOERE REGION NORWAY	797.00	3.50	351.90	145.40	N
11	2014-023:04.32.50.0	61.22	4.90	2.70	NORTHERN NORTH SEA	807.60	9.30	363.90	446.20	N
12	2014-030:14.20.28.0	58.44	6.10	1.38	ROGALAND NORWAY	661.80	3.60	399.70	21.60	-
13	2014-043:14.22.54.0	58.05	6.87	1.92	SKAGERRAK	684.20	3.50	400.50	14.50	-
14	2014-044:02.13.16.0	53.68	6.56	2.54	NORTHERN LOWER SAXONY AND HOLSTEIN	655.90	53.10	841.50	145.10	-
15	2014-060:13.58.05.0	57.02	7.34	2.64	EASTERN NORTH SEA	678.20	49.10	479.60	115.00	-
16	2014-072:14.20.30.0	58.24	6.30	1.22	ROGALAND NORWAY	662.20	5.80	406.70	28.90	-
17	2014-084:11.55.26.0	60.98	6.25	1.29	SOGN-MOERE REGION NORWAY	837.10	3.30	289.10	25.30	-
18	2014-084:18.19.55.0	57.09	7.28	1.65	EASTERN NORTH SEA	676.20	6.30	474.60	13.90	-
19	2014-092:17.46.32.0	58.64	5.90	1.64	ROGALAND NORWAY	662.30	4.60	394.20	31.80	-
20	2014-098:06.50.13.0	62.27	3.76	2.79	MOERE SHELF	869.50	8.70	448.60	50.50	-
21	2014-120:13.19.24.0	58.44	6.10	1.26	ROGALAND NORWAY	661.80	4.10	399.70	15.70	-
22	2014-122:14.06.55.0	61.39	7.39	0.58	SOGN-MOERE REGION NORWAY	913.40	4.30	235.80	14.70	X
23	2014-122:18.13.00.0	53.40	2.67	2.96	SOUTHWESTERN NORTH SEA	435.40	359.20	976.90	8.20	N
24	2014-125:13.34.36.0	62.34	4.05	2.51	MOERE SHELF	884.00	4.40	436.50	35.40	N
25	2014-128:13.20.31.0	58.05	6.87	1.49	SKAGERRAK	684.20	4.80	400.50	25.90	-
26	2014-143:13.18.51.0	58.44	6.48	1.90	ROGALAND NORWAY	681.80	4.10	383.20	27.50	N
27	2014-154:13.17.25.0	58.24	6.68	1.36	AGDER NORWAY	682.60	4.90	391.20	19.00	-
28	2014-160:18.01.26.0	64.01	6.35	1.80	VOERING BASIN	1103.30	3.90	453.00	28.30	N
29	2014-161:13.19.48.0	58.24	6.30	1.42	ROGALAND NORWAY	662.20	4.30	406.70	18.10	-
30	2014-199:13.23.18.0	58.24	6.30	1.78	ROGALAND NORWAY	662.20	9.60	406.70	42.40	-
31	2014-218:12.33.37.0	53.59	-1.82	2.17	PENNINES	212.80	14.70	1131.40	4.80	X
32	2014-228:01.18.42.0	57.02	6.97	1.38	EASTERN NORTH SEA	656.40	13.90	490.40	14.70	-
33	2014-241:09.24.56.0	55.49	7.88	1.44	EASTERN NORTH SEA	699.00	9.30	622.50	11.90	-
34	2014-241:13.19.10.0	58.24	6.68	1.90	AGDER NORWAY	682.60	6.30	391.20	27.00	N
35	2014-249:16.56.37.0	60.15	6.03	2.50	HARDANGER NORWAY	765.90	5.60	310.40	218.60	N
36	2014-250:05.01.56.0	58.02	6.80	1.96	SKAGERRAK	679.80	4.70	404.70	21.40	N
37	2014-252:13.14.52.0	58.24	6.68	1.41	AGDER NORWAY	682.60	3.50	391.20	23.50	-
38	2014-266:13.19.38.0	58.44	6.10	1.28	ROGALAND NORWAY	661.80	4.00	399.70	26.00	-
39	2014-273:10.59.04.0	58.65	0.47	2.89	VIKING GRABEN	430.10	44.80	665.10	51.00	N
40	2014-275:13.18.49.0	58.44	6.10	1.69	ROGALAND NORWAY	661.80	5.40	399.70	20.40	-

We note that most of the events listed in Table 6.1.1 have not been included in the NORSAR reviewed regional bulletin. This is mainly because the event magnitude is below the threshold for such analysis. However, more importantly, such events can now be extracted and presented to the analyst without generating a large number of false alarms which would previously have been the case (this is because of the restrictive criteria that are now applied to generate Table 6.1.1). The two 'false alarms' in Table 6.1.1 are easily removed by the analyst; they might in fact be real events, but would be of no interest to monitoring the North Sea area.

A map showing the location of the 38 acceptable seismic events in Table 6.1.1 is shown in Figure 6.1.7. We note from this figure that the geographical distribution of the detected events is as expected, considering the overall seismicity pattern shown in Figure 6.1.2. The main seismicity is near the Norwegian west coast. As a consequence, the epicentral distances of the detected events are generally larger for EKA than for NRS, and the signal-to-noise ratio at NRS is in most cases somewhat higher than at EKA. Figure 6.1.8 shows SNR at the two arrays adjusted for event magnitude as a function of distance, and confirms a slightly better detectability for NRS for this event set. Nevertheless, we can conclude that EKA has an excellent performance for event detectability in the North Sea region, and would provide a very valuable supplement to the NORSAR regional GBF processing.

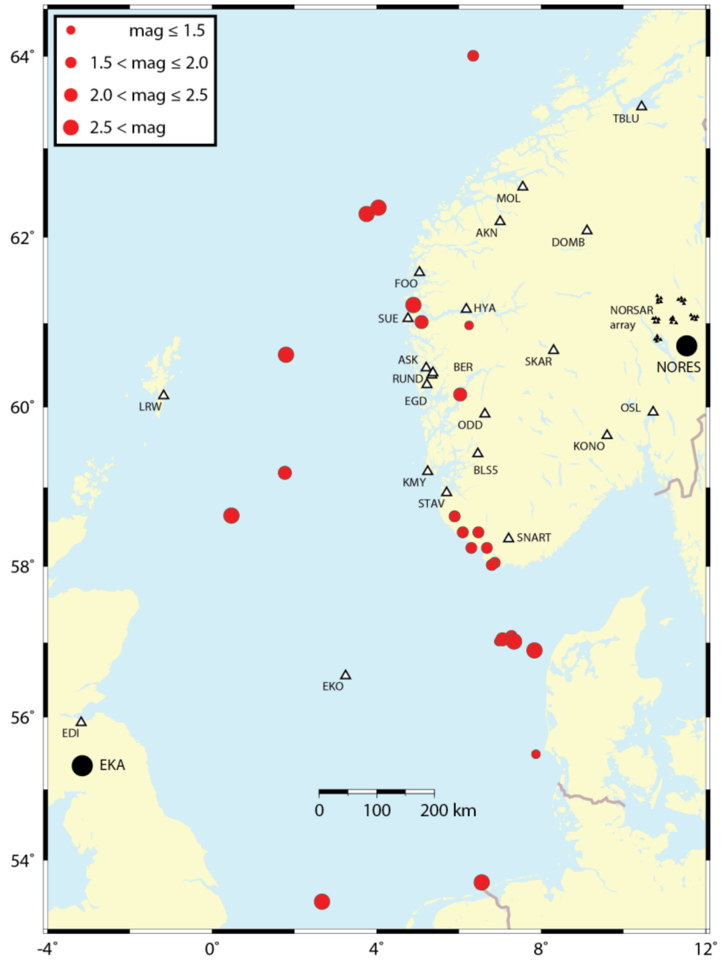


Fig. 6.1.7 Automatic location of the 38 acceptable seismic events listed in Table 6.1.1. Note that because the GBF procedure is grid-based, some events nearby each other will be located at the same grid point in the automated GBF procedure.

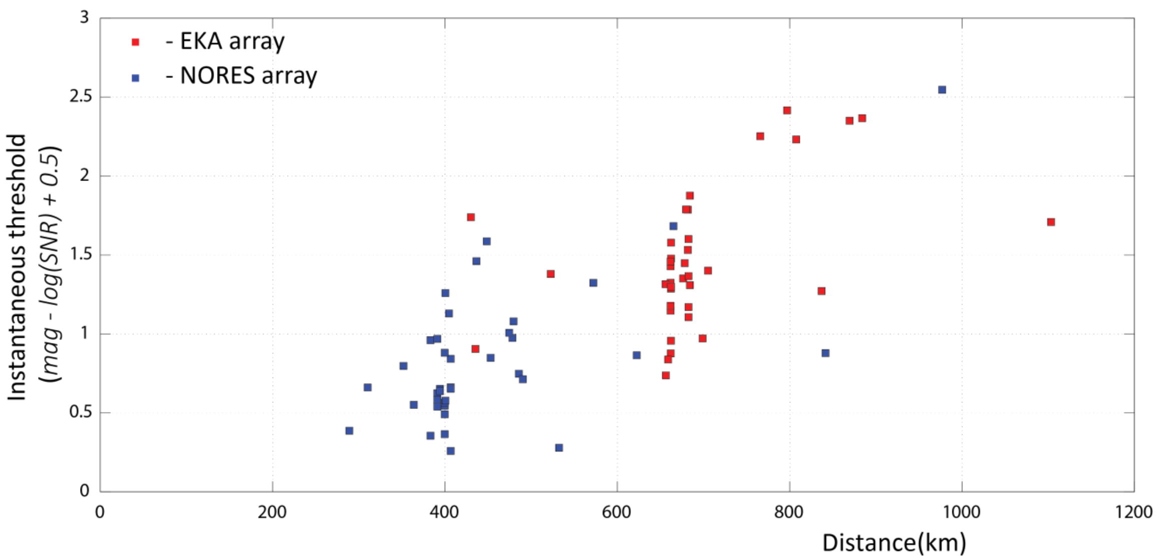


Fig. 6.1.8. SNR at the two arrays adjusted for event magnitude as a function of distance,

6.1.4 Conclusions

Our conclusions from this study are as follows:

- The EKA functions as an excellent regional array, and could be a very valuable supplement to NORSAR's regional seismic network.
- Inclusion of EKA in the NORSAR GBF processing works very well. EKA detections have been automatically associated with many seismic events already detected by the regular GBF processing during the time period.
- With EKA included, the NORSAR GBF detection list contains many small events in the North Sea region currently not being analyzed interactively at NORSAR. Thus, the inclusion of EKA would contribute to a more complete reviewed NORSAR regional bulletin.
- In addition, the inclusion of EKA results in many new seismic events being detected. However, most of the new events are one-array events (P and S from EKA) in or close to Britain, and are therefore not candidates for inclusion in the NORSAR regional bulletin.
- Addition of EKA gives a much improved azimuthal coverage for detected events, thus providing more accurate event locations.
- The array beams formed with EKA data give significant SNR improvements, thus enabling more precise phase arrival time estimates.

There are still some remaining improvements that could be considered. Thus, the EKA array data is currently processed using a generic recipe. Improved performance can be achieved by conducting a tuning study. The automatically calculated magnitudes at EKA have not yet been calibrated, and this obviously needs to be done. There might also be a need for considering Lg blockage across the Viking Graben (Kennett et al., 1985) when forming the generalized beams. Such blocking features occur also in other areas covered by the NORSAR regional processing, and should be considered there as well.

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