NORSAR

NORSAR Scientific Report No. 1-2009

Semiannual Technical Summary

1 July - 31 December 2008

Frode Ringdal (ed.)

Kjeller, February 2009

6.4 Seismic arrays in Earthquake Early Warning Systems (EEWS)

6.4.1 Introduction

Main parts of the following contribution were compiled during NORSAR's participation in the SAFER project, which is mainly funded under the Sixth Framework Programme of the European Commission (Project Number 036935). Within this project, NORSAR investigated the application of array techniques to EEWS installations. In the following, some results of this study are documented.

A seismic array can be described as a set of seismic sensors with common time base and instrumentation. The data of such an installation are then usually analyzed together by applying the well known algorithms fk-analysis and beamforming. The advantage of applying seismic array techniques in EEWS is connected with the capability of an array not only to observe a seismic signal but also to measure its propagation direction and apparent velocity. Moreover, during the last four decades, arrays also played a very important role in many basic studies about the Earth. However, the capability of an array to measure the backazimuth (BAZ) and apparent velocity with sufficient accuracy and to suppress other than the target signals is very much depending on the array geometry and the number of its sensors. Therefore, not each array is equally suitable for an Earthquake Early Warning System (EEWS). Further details about array geometries and their characteristics can be found *e.g.*, in Douglas (2002), Rost & Thomas (2002) or Schweitzer *et al.* (2002).

In the beginning, we briefly discuss the development of event-location techniques with seismic arrays and the contribution of arrays to fast event location. Then, we will focus on the usage of seismic arrays as EEWSs in general, and in particular on real-time algorithms and discuss the advantages and disadvantages of applying array-analysis techniques as input for any EEWS.

6.4.2 Locating seismic events with arrays

As already mentioned, seismic arrays not only observe amplitudes and onset times of seismic signals, but can also measure their corresponding apparent velocities and BAZs. The latter two parameters are essential in locating the source of observed seismic onsets and thereby locating the seismic event.

Teleseismic event location

Benndorf (1906; 1907) published that in the case of a spherically symmetric Earth model apparent velocities (or the seismic ray parameters) are constant along their whole ray path through the Earth (Benndorf's Law). If the velocities inside the Earth are known, it can easily be shown that the ray parameter of seismic onsets changes with the epicentral distance and that an observed ray parameter (or apparent velocity) can directly be inverted for the epicentral distance. For modern spherically symmetric Earth models and seismic arrays of at least 10 km aperture, this principle works fine for first arriving P-type onsets from seismic events at teleseismic distances (*i.e.*, from about 25˚ to about 100˚ epicentral distance). Events at shorter distances are hard to locate because the derivative of the apparent velocity with respect to distance is very small and triplications of the travel-time curve do not allow for a unique correspondence between apparent velocity and distance. At distances beyond the Earth's shadow zone, the interpretation of the different core-phase onsets is also quite difficult and limits the location capabilities of a seismic array. Knowing the epicentral distance, the observed BAZ can then be used to define the epicentral coordinates.

The described event location technique has been in use at least since the 1960s and a quick look in the bulletins of the International Seismological Centre shows the huge amount of reported teleseismic event locations made with e.g., the Large Aperture Seismic Array (LASA) in Montana, USA, the Yellowknife Array (YKA) in Northern Canada, the Gräfenberg Array (GRF) in Bavaria, Germany or the large Norwegian Seismic Array (NOA) in Southern Norway. All results of the automatic array processing of the NOA array can be found at http://www.norsardata.no/NDC/bulletins/dpep.

Regional arrays

As mentioned, the inversion of an apparent velocity into an epicentral distance does not work for local or regional distances, as observed apparent velocities of direct phases are not changing with epicentral distance. However, the apparent velocities are usually different for the different local and regional seismic phase types, Pg, Pn, Sn, or Sg. Therefore, the observed apparent velocity of a seismic onset can be used to characterize the seismic phase.

In the case that different seismic phases from the same seismic event are observed, the travel-time differences between the different phases can be used to determine the epicentral distance and with the observed BAZ the event can be located. This approach was already used by Abt (1907) in the case of teleseismic events. First, he was making apparent velocity and BAZ measurements and then he used the travel-time difference between the first P- and the first S-phase onset, for which the distance dependence was better known, to define the epicentral distance and together with the BAZ he determined the location of the event.

Early seismic arrays were built with an aperture and configuration favorable for teleseismic observations and they were not optimized to handle observations from regional or local events. Therefore, the concept of small-aperture arrays with apertures of only a couple of kilometers was developed in the early 1980s and firstly tested with the NORES array, collocated with one of the NORSAR array sites (Mykkeltveit *et al.*, 1983).

Routine processing of small-aperture array data at NORSAR

For the NORES array, a three step data-analysis and event-location algorithm (called RONAPP) was developed (Mykkeltveit & Bungum, 1984), which utilizes the aforementioned combination of phase identification and travel-time difference measurements and which is in principle the base for many of today’s installed small and middle aperture event-location algorithms. This so-called DP/EP automatic array data analysis algorithm was further developed at NORSAR during the last decades (Fyen, 1989; 2001a; 2001b; Kværna & Doornbos, 1986; Kværna & Ringdal, 1986; Mykkeltveit & Bungum, 1984; Ødegaard *et al.*, 1990; Schweitzer, 1994; 1998; 2001b; 2003b; Schweitzer & Kværna, 2006; Schweitzer *et al.*, 2002) and can shortly be described as a three step process:

- Detection Processing (DP), *i.e.*, performing STA/LTA triggering on a number of predefined beams;
- Signal Attribute Processing (SAP), *i.e.*, performing signal feature extraction of detected signals; and

- Event Processing (EP), *i.e.*, performing phase association, event location and event plotting based on the RONAPP processing (Mykkeltveit & Bungum, 1984).

A detailed description of these processing steps can be found in Schweitzer *et al.* (2002) and results of the automated regional array processing at NORSAR can be found at http://www.norsardata.no/NDC/bulletins/dpep.

Network of arrays

It became very soon obvious that the location precision of single small aperture arrays is quite limited. After building up a network of small aperture arrays in Northern and Central Europe during the late 1980s and early 1990s, a joint interpretation of observations from several small-aperture arrays could be tested. One successful approach became the Generalized Beam Forming (GBF) location algorithm. This algorithm developed at NORSAR can automatically utilize the results of several seismic arrays in a common bulletin (Ringdal & Kværna, 1989; Kværna *et al.* 1999). Today, data from the highly sensitive regional arrays ARCES, FINES, HFS, SPITS, and NORES, and the teleseismic NORSAR array (NOA) are automatically processed in on-line mode applying this regional and local event-location process (http://www.norsardata.no/NDC/bulletins/gbf).

6.4.3 Contributions of arrays to fast event locations

Single array results

As already discussed, it is possible to locate seismic events with data observed by one or more seismic arrays. However, in the case of any fast event location algorithm array analysis can only contribute if the whole data processing is automated. On the other hand, the recorded data volume is very large, thus requiring automated data processing techniques. Therefore, array data processing algorithms were as much as possible automated since the 1960s. For example, the program package used for the NORSAR array was mostly developed in the 1970s and 1980s and later adapted to many other array installations (Fyen, 1989; 2001a; 2001b).

After international exchange of emails was becoming more reliable and common in the early 1990s, it became possible to report event locations or strong P-phase observations based on fully automatically data processing algorithms. Thereby, results from the NORSAR, YKA, or the GERES array were automatically sent to *e.g.*, the USGS for its Quick Epicenter Determinations (QEDs), the European-Mediterranean Seismological Center (EMSC), the Swiss Seismological Service (SED), and the wider interested seismological community.

The Fast Earthquake Information Service (FEIS) algorithm

At the University of Bochum a special alert system was developed in the early 1990s, which combined the mentioned single array observations with recordings of the newly at that time installed German Regional Seismological Network (GRSN). The so-called Fast Earthquake Information Service (FEIS) algorithm (Schulte-Theis *et al.*, 1995; Harjes *et al.*, 1996) was triggered by strong local or regional events observed by the GERES array. For this, the data of the regional GERES array were automatically analyzed in real time by applying the DP/EP array software developed at NORSAR (Fyen, 1989; 2001a; 2001b). After each automatic GERES location with a local magnitude above 3.0, the FEIS algorithm was triggered, consisting of the following steps:

- recalculation of an initial location from the GERES data alone;
- calculation of theoretical onset times for regional phases (Pn, Pg, Sn, Sg) at all GRSN stations;
- polling of all GRSN-detection lists via telecommunication lines for a larger time interval around the assumed arrival times;
- searching a small time interval around the theoretical onset times for Pg or Pn detections, depending on the epicentral distance;
- in the case that a P-type phase could be associated, the detection lists were searched for possible S-type detections in a distance-depending predefined time window;
- relocation of the event with the GERES-observation parameters (phase names, onset times, BAZs) and the applicable GRSN detections;
- in the case of a stable location result, the determined location was distributed automatically via email about 30 minutes after the event as FEIS-alert to the EMSC or other interested addresses in Europe.

A comparison with PDE (USGS) locations indicates that the automatic FEIS-relocation procedure significantly improved the automatically achieved location accuracy, in particular for these events which occurred within the GRSN.

NORSAR's Event Warning System (NEWS)

Since 2000, a new quick event-location system was developed at NORSAR to provide fast and reliable solutions in the case of strong events: NORSAR's Event Warning System (NEWS) (Schweitzer, 2003a). The whole NEWS system is based on high Signal-to-Noise Ratio (SNR) detections; whenever one of the contributing arrays observes a P-type onset with an SNR larger than a predefined threshold, the NEWS process is initialising.

Once triggered, the NEWS process searches the automatic result lists of all other available arrays for corresponding onsets. Corresponding in this context means that the other onsets have to come from a backazimuth, and with an apparent velocity, which is consistent with the triggering onset. Formulating robust rules, for which onsets can eventually be associated with the same event, was a quite cumbersome procedure. However, as implemented today, these rules are built on travel-time differences between the onset times at the different stations, measured backazimuth and apparent velocity of the signals, and SNR of the onsets. In the case of a presumably local or regional event, NEWS also searches for S-type onsets in the onset lists of the arrays.

Source location with the NEWS algorithm

After all available lists are searched the NEWS process locates the seismic event. To make this automatic event location as robust as possible, onset times and apparent velocity values are only used from first P and S arrivals. However, to use as much as possible information from the seismic arrays, all onsets in compliance with the selection rules and the measured backazimuth values are used to locate the event. Depending on the mean apparent velocity of all detected P onsets, the program defines the event as probably regional, or as near, far or very far teleseismic. Then, together with the mean backazimuth estimation, an initial source region is chosen. Depending on this initial solution, either a regional or a global velocity model is used to locate the event. The observed P amplitudes can be used to calculate an event magnitude.

For the determination of the source parameters NORSAR's location program HYPOSAT (Schweitzer, 2001a) is used. With the limited amount of data available for locating the event, the event's depth cannot be resolved and has therefore to be fixed to a predefined value. However, until now, such preliminary locations have been sufficient for preliminary information to the public in the case of local or regional events.

In the case of teleseismic events, the NEWS reports are often listed together with only a few other alert-messages from distributing institutes on the Real Time Seismicity Page of the EMSC (http://www.emsc-csem.org/Welcome.html) and thereby help the EMSC to locate such events more accurately.

Although the used network of seismic arrays has an aperture of about 18 degrees in the north-south direction, teleseismic events are usually observed over only a very small azimuth range. Therefore, the small number of available observations produces solutions with limited accuracy and large error bars, and some events are even not locatable. This is in particular true for events in the South Pacific, for which only PKP-type onsets can be observed.

Dissemination of NEWS results

On average, NEWS solutions are available between a few and up to about 10 minutes after the first P onsets have been recorded at one of the seismic arrays. Since January 2001, a listing of the most recent NEWS solutions has been available on the web (http://www.norsar.no/bulletins/alert/). In summer 2002, NORSAR started to send the NEWS solutions to interested data centers, which also work on quick epicenter determinations in Europe, such as the EMSC in Bruyères-le-Châtel, France and the European data center for broadband data ORFEUS in De Bilt, The Netherlands. Since summer 2007, NEWS alerts for events observed with magnitudes larger or equal to 6.0 are also automatically reported to World Agency of Planetary Monitoring and Earthquake Risk Reduction in Geneva, Switzerland and since summer 2008, the NEWS alerts are also going to the International Seismological Centre (ISC) in Thatcham, UK.

The delay of several minutes between the source time and the dissemination of source parameters of regional events by today's NEWS implementation is due to several factors:

- usually, the distance between a seismic event and the closest array recording it is on the order of several hundreds of kilometers
- it takes several additional minutes until other arrays of the sparse network of arrays in Northern Europe can record the event;
- to achieve a more stable solution for the event location the NEWS algorithm is implemented in such a way that it also waits for possible S-type onsets;
- the location algorithm HYPOSAT (Schweitzer, 2001a) used for locating the event is not yet optimized for short computation time.

6.4.4 Usage of seismic arrays to monitor an EEWS relevant site

With its unique capability to measure not only onset times and amplitudes, but also BAZs and apparent velocities of seismic onsets, an array gives us several possibilities to locate an event. The only question is, which algorithm and data processing scheme should be used to provide quick locations for an EEWS. Working with the above mentioned methods and software packages, one can conclude that with today's computer capacities the most critical parameter for using seismic arrays in an EEWS is the epicentral distance to the array installation(s).

All discussed algorithms are on today's computers so fast that the actual calculation times for the different algorithms do not really contribute to EEWS delays. More important are the actual transmission times of seismic signals since all data connections algorithms work with data frames containing a specific amount of data. The delay time between the actual recording of a signal and its arrival at a data center can vary between seconds and minutes and has to be added to the EEWS times achievable by the discussed location algorithms.

The single array case

In the case of single array locations at local or near regional distances, the travel-time difference between source and arrival time of the first P phase is in the order of tens of seconds for local or near regional events. Additional tens of seconds will be needed to record the first S-onset, necessary for calculating the epicentral distance.

Therefore, such an array used as an EEWS tool will most likely need more time to locate the event than a traditional seismic network installed in the area of interest. The situation changes in many cases where several seismic active areas or a longer tectonic fault contribute to seismic hazard. Dense, local networks cannot be installed at all places and in particular if more remote or off-shore located zones contribute to a hazard scenario, single array installations can contribute, within a few minutes, with quite reliable event locations for all events within some hundred kilometers epicentral distance. However, as shown by Gibbons *et al.* (2005), a single array can be tuned for a specific target area and the resulting location precision can become as high as that of a local network, assuming that sufficient calibration information is available. This is in particular of interest in the case of monitoring aftershock sequence of a very large earthquake.

A single array and a sparse national network

In the case that data from an array and additionally a national or local network are available, a FEIS-type algorithm can be used. Knowing the BAZ and apparent velocity of the first P-type onset directly gives information about the direction in which the event occurred and if it was at a local or a regional distance. For regional events, the first P onset should have an apparent velocity typical for Pn phases and for local events typical for Pg onsets, respectively. With this information, the array result for the first P onset directly indicates, which single station records should be added to achieve a fast and reliable event location.

An EEWS based on a single array and a sparse network can provide a first, quick and reliable event location within the first minute after the event occurred as long as one of the network stations is located as close as the array or closer to the event.

Multiple array configuration

In the case of observations from two or more arrays, a GBF- or NEWS-type algorithm can be implemented. Recording one onset from each array with a BAZ estimate is already sufficient to locate the source area. If the target fault zone is located between two arrays, which have a distance of about 200 km from each other, such an installation is sufficient to locate the main shock and the whole aftershock sequence on the fault zone within about 30 seconds. Events, which are not located between the two arrays, will be located within 20 s plus the absolute travel time of the first P onset to one of the arrays.

This scenario of course assumes that the data of the two arrays are available in real time for the automatic array processing software (DP/EP). The location capabilities will increase with a larger number of small-aperture arrays. In such cases, different arrays may be combined to monitor different target areas.

Johannes Schweitzer

References

Abt, A. (1907). Vergleichung seismischer Registrierungen von Göttingen und Essen (Ruhr). Inaugural-Dissertation (Ph.D. thesis), Philosophische Fakultät, Georg-August-Universität zu Göttingen, Göttingen 1907, 26 pp. + curriculum vitae.

Benndorf, H. (1905). Über die Art der Fortpflanzung der Erdbebenwellen im Erdinneren. 1. Mitteilung. Sitzungsberichte der Kaiserlichen Akademie in Wien. Mathematisch-Naturwissenschaftliche Klasse 114, Mitteilungen der Erdbebenkommission, Neue Folge **29**, 1-42.

Benndorf, H. (1906). Über die Art der Fortpflanzung der Erdbebenwellen im Erdinneren. 2. Mitteilung. Sitzungsberichte der Kaiserlichen Akademie in Wien. Mathematisch-Naturwissenschaftliche Klasse 115, Mitteilungen der Erdbebenkommission, Neue Folge **31**, 1-24.

Douglas, A. (2002). Seismometer arrays – their use in earthquake and test ban seismology. In: Lee, W.H.K., H. Kanamori, P.C. Jennings & C. Kisslinger (eds.) (2002): Handbook of Earthquake and Engineering Seismology. Academic Press., Vol. A, 357-367.

Fyen, J. (1989). Event processor program package. NORSAR Sci. Rep. **2-88/89**,117-123.

Fyen, J. (2001a). NORSAR seismic event processing – user guide and command reference. NORSAR (contribution 748), Kjeller, Norway.

Fyen, J. (2001b). NORSAR seismic detection processing – user guide and command reference. NORSAR (contribution 731), Kjeller, Norway.

Gibbons, S.J., T. Kværna & F. Ringdal (2005). Monitoring of seismic events from a specific source region using single a single regional array: A case study. J. Seism. **9**, 277-294.

Harjes, H.-P., H. Schulte-Theis, M.L. Jost & J. Schweitzer (1996). Fast Earthquake Information Service (FEIS). CSEM / EMSC, Newsletter, **9**, 2–4, 1996.

Kværna, T. & D.J. Doornbos (1986). An integrated approach to slowness analysis with arrays and three-component stations. NORSAR Sci. Rep. **2-85/86**, 60-69.

Kværna, T. & F. Ringdal (1986). Stability of various f-k estimation techniques. NORSAR Sci. Rep. **1-86/87**, 29-40.

Kværna, T., J. Schweitzer, L. Taylor & F. Ringdal (1999). Monitoring of the European Arctic using regional generalized beamforming. NORSAR Sci. Rep. **2–98/99**,78–94.

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

Mykkeltveit, S., K. Åstebøl, D.J. Doornbos & E.S. Husebye (1983). Seismic array configuration optimization. Bull. Seism. Soc. Am. **73**, 173-186.

Ødegaard, E., D.J. Dooornbos & T. Kværna (1990). Surface Topographic effects at arrays and three-component stations. Bull. Seism. Soc. Am. **80**, 2214-2226.

Ringdal, F. & T. Kværna (1989). A multi-channel processing approach to real time network detection, phase association, and threshold monitoring. Bull. Seism. Soc. Am. **79**, 1927-1940.

Rost, S. & C. Thomas (2002). Array Seismology: Methods and applications. Rev. Geophys., **40**(3), 1008, doi:10.1029/2000RG000100.

Schulte-Theis, H., M.L. Jost & J. Schweitzer (1995). Fast earthquake information service (FEIS): optimized location of seismic events in Europe. In: Advanced waveform research methods for GERESS recordings. Scientific Report 4, 1 December 1994 – 30 June 1995, DARPA Grant MDA 972–93–1–0022, 17–28, 1995

Schweitzer, J. (1994). Some improvements of the detector / SigPro-system at NORSAR. NORSAR Sci. Rep. **2–93/94**, 128–139.

Schweitzer, J. (1998). Tuning the automatic data processing for the Spitsbergen array (SPITS). NORSAR Sci. Rep. **1-98/99**, 110-125.

Schweitzer, J. (2001a). HYPOSAT – an enhanced routine to locate seismic events. Pure appl. geophys. **158**, 277-289.

Schweitzer, J. (2001b). Slowness corrections – one way to improve IDC products. Pure appl. geophys. **158**, 375-396.

Schweitzer, J. (2003a). NORSAR’s event warning system (NEWS). NORSAR Sci. Rep. **1–2003**, 27-31.

Schweitzer, J. (2003b). Upgrading the ARCES (PS 28) on-line data processing system. NORSAR Sci. Rep. **1–2003**, 33-43.

Schweitzer, J. & T. Kværna (2006). Improvements to SPITS regional S-phase detection; coherent beamforming of rotated horizontal components. NORSAR Sci. Rep. **2–2006**, 47-58.

Schweitzer, J., J. Fyen, S. Mykkeltveit & T. Kværna (2002). Chapter 9: Seismic Arrays. In: Bormann, P. (ed.) (2002). IASPEI New Manual of Seismological Observatory Practice (NMSOP), GeoForschungsZentrum Potsdam, Vol. 1, 52 pp.