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Automatic Location of Teleseismic Events with Local Network

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Abstract

This article gives a description of an automatic location method for teleseismic events. The method is based on the standard procedure of forming slowness vector of tripartite array and computing an event location using it. Maximum number of tripartite subarrays are formed using all stations of the network. Event location is computed with each subarray and results are combined to get the final location. Output of the system is a fully automatic bulletin of teleseismic events.

The arrival onsets are obtained automatically using an event detector and refined with an onset estimator. The data are preprocessed using 7 band pass filters. The whole data processing procedure is repeated separately with each filtering band to find the best possible solution for event location.

The method has proven to give a reliable estimation of event location even for small teleseismic events. During a test period of 317 days the system located 857 events that were found also in PDE bulletins. Half of the events had mb ≤ 4.8. The system could locate 350 events which were not located manually by analysts. The median of location difference compared to the PDE bulletins was 297.0km for the events accepted to the automatic bulletin. The requirements for station network are simple. 5 z-component short period stations are enough for running the system.

1. *Introduction*

Automatic location of seismic events has been a target of considerable interest in the seismological society in the 1980s and 1990s. The cost of keeping large analysis personnel and limited funding suppress possibilities to analyse all recorded events interactively. The number of stations producing digital data is rising. Methods in signal analysis and event detection are improving, which leads to larger amount of detected events. The development of more efficient computers has made it possible to create systems and use methods for automatic location, which were not realizable in the previous decades.

Polarization analysis offers best method to locate events with one three component station by providing direction of signal and information for phase recognition. Several studies presenting automatic single station location methods based on polarization analysis have been published recently (*Ruud and Husebye*, 1992, *Kedrov* and *Ovtchinnikov*, 1990, Roberts et al., 1989). Single station systems are more suitable for locating regional than teleseismic events because the determination of distance is difficult if no later phases are available, which often is the fact with teleseismic events. It is possible to compute incidence angle or apparent surface velocity from three-component seismogram but determination of distance is relatively inaccurate with them due to high error levels (*Harris*, 1990). Azimuth errors can also give significant location errors with single three-component station (*Suteau-Henson*, 1990). Especially low signal-to-noise ratio (SNR) weakens performance of polarization based location methods with three-component data. Using a network of three-component stations reduces the effects of these problems.

In general array data offers best possibilities for automatic seismic event location. In the 1960s and 1970s several arrays were build up in various countries and a lot of work was done to improve their location capabilities (*Greenfield* and *Sheppard*, 1969, *Gjøystdal et al.*, 1973, *Brown*, 1973, *Berteussen*, 1974, *Shapira* and *Båth*, 1976). Most of these were developed primarily for monitoring teleseismic events. Negotiations on a Comprehensive Test Ban Treaty in late 1970s and start of the next decade caused a shift of interest from teleseismic to regional distances (*Mykkeltveit et al.*, 1990). After that several regional arrays have been established in Europe; NORESS and ARCESS in Norway, FINESA in Finland, GERESS in Germany and two new arrays in Kola peninsula and Spitsbergen run by NORSAR. Though these arrays were planned with main focus on local and regional events they are also very useful in locating teleseismic events. Combined use of regional arrays and other stations in the Intelligent Monitoring System (*Bache et al.*, 1990) has proved to be a powerful method in locating teleseismic events automatically.

The approach presented in this paper gives a simple method to locate teleseismic events automatically with a local network of seismic stations. The requirements for the network are simple. 5 single channel z-component short period stations are enough for running the system. This means the method can be used even with relatively simple low cost networks. The system has been running with 8 stations of Finnish National Seismic Network FINET. The operation of the current version started at Dec. 1. 1991 even though the first version dates back to 1989. The operation started with only 6 stations (KEF, SUF, KAF, PVF, PKK, NUR). The network configuration was not very suitable for the system at start but the performance improved strongly after stations VAF and JOF were added to it. The location of stations is presented in Figure 1.

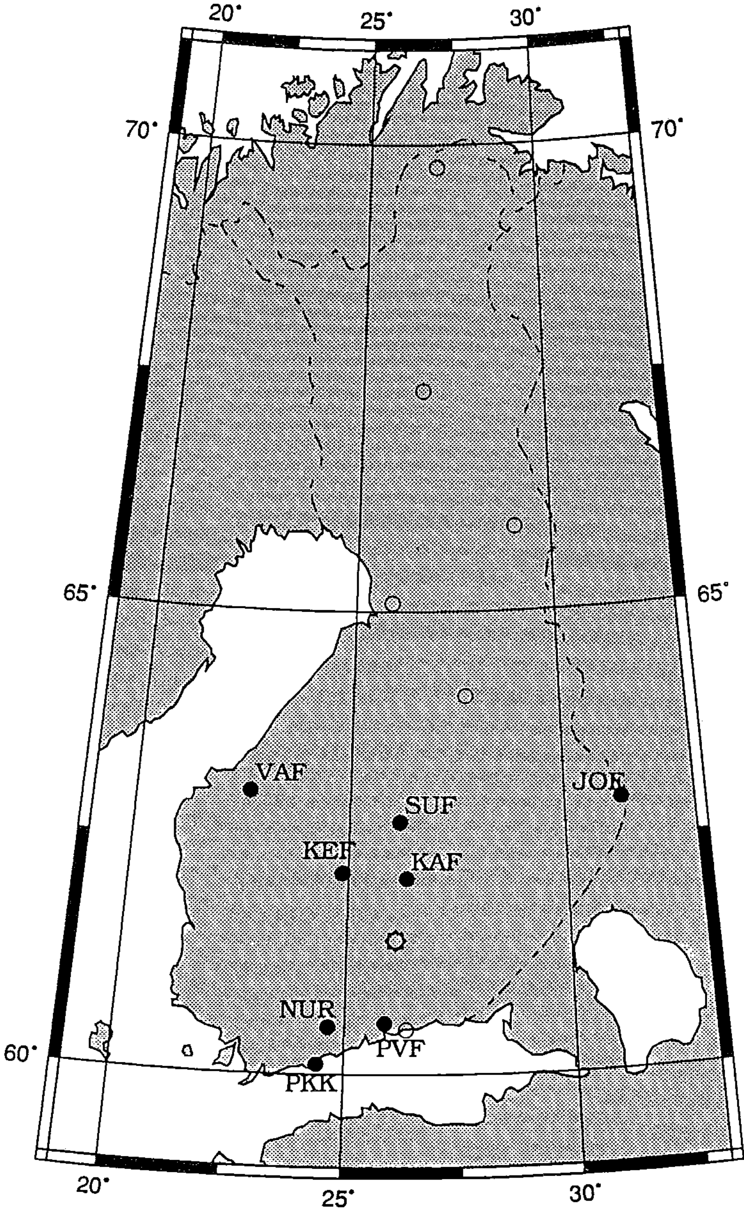

Fig. 1. The stations used in the location system are marked with solid circles.
Other seismograph stations in Finland are marked with open circles. Regional array FINESS is denoted with open star.

2. *Data processing*

The data are collected according to results of automatic detector system. Data of 3 stations in Central Finland (KEF, SUF, NUR) are run through a single channel signal detector after band pass (BP) filtering. Data of each station are prefiltered with 7 narrow BP filters. The filters are selected so that the intersections of gain curves of each two neighbouring filter bands lie at the same dB level. The filter bands are found in Table 1. Single channel detections of each filtering band are collected together and a voting system is used to pick possible events from numerous single channel detections. Number of single channel detections varies from some dozens to 1000 per day depending on the station and filtering band. Similar procedure is done with 3 stations in southern Finland (PVF, PKK, NUR) but only with 2 high frequency filtering bands. Their contribution to the detection list consists mostly of local events. So they are neglected in this presentation. The detector which is used with data is a peak-to-through detector originally developed by *Murdock* and *Hutt* (1983). The C language version currently in use is made by *Murdock* and *Halbert* (1987). The detector is often referred in literature as SRO detector.

Table 1. The BP filter bands used in automatic detector and locator system. The frequency filtering was performed using Butterworth filters of third order.

filter channel	low frequency cut-off (Hz)	high frequency cut-off (Hz)
ch1	0.5000	0.9555
ch2	0.6912	1.3208
ch3	0.9555	1.8258
ch4	1.3208	2.5240
ch5	1.8258	3.4890
ch6	2.5240	4.8239
ch7	3.4890	6.6667

The data sections of detected events are collected from all stations for further analysis. The data of each station are run through SRO detector prefiltered with the same BP filters as described previously. This time detector is tuned to be very sensitive, so that even the weakest signals are found. This can lead to several onsets per station for one event. A data-adaptive onset estimator (*Pisarenko et al.*, 1987, *Tarvainen*, 1991) is used to get more accurate onset times. The algorithm of onset estimator is based on adapting parameters of autoregressive processes, which describe signal and noise.

The corrected onset times of each filtering band are used as sets of possible arrival times, which contain the true P-wave arrival times among false alarms. The automatic location procedure is repeated with each set of onset times resulting up to 7 possible solutions for the event epicenter. These solutions are studied and they are given a reliability factor (RF). The solution with highest RF value is chosen to be the final location for the event. The location algorithm does not have knowledge whether the data set includes a teleseismic event or not. The detection resulting to running the automatic locator might be a local event or a false alarm. A low RF value implies that event is too weak to compute an accurate location or that it is not a real teleseismic event.

The parallel use of 7 filtering bands involves some redundancy. Many of the solutions are comparably good with a clear event, but by computing several locations and choosing the best the accuracy is improved. The best solution is produced by filter band which provides not only the most accurate but also the most analogous onset time measurements. This is not always the band of average center frequencies of the signals. So choosing only one filtering band for each event would be a difficult task that could even deteriorate the results.

4. *Algorithm*

The scope of this work includes distances from 10° to 103°, the area from which the first incoming wave is a direct P-wave, which has travelled through mantle (*Kulhànek*, 1990). From closer range slowness vector does not explicitly tell the distance from the epicenter. From longer distances, when first arriving phase is a diffracted P or PKP, gradient of slowness with respect to distance is so small that accurate determination of distance is difficult. Also automatic recognition of different branches of PKP-waves is not part of this work.

The algorithm is presented as block diagram in Figure 2. The fundamental location method used here is a variation of the popular procedure originally attributed to *Geiger* (1910). The slowness vector of a tripartite subarray is computed using arrival time differences. The arriving wavefront is assumed to be a plane wave and the arrival times are fitted to the plane with least squares method (*Tarvainen* and *Heikkinen*, 1993). The slowness of P-wave gives distance with help of travel time tables and location is computed using it and backazimuth. Locations are computed using onset time differences of each possible 3 station triangle and each possible combination of onsets. This results a set L^T of locations, referred as trial locations l_i^T hereafter.

$$L^T = \{l_1^T, \ldots l_{N_T}^T\}; \qquad L_i^T = (lat_i, lon_i) \tag{1}$$

N_T is the number of trial locations and lat_i, lon_i are the coordinates of the ith trial location l_i^T. Many of the 3 onset combinations do not produce a location at all since most of the onsets are false alarms or coda detections and time differences do not correspond to slowness scale of P-wave. Consequently, many of the obtained trial locations l_i^T in L^T are erroneous. If the seismogram contains clear enough teleseismic event, the real P-wave arrivals are among the onsets, and so is a set $L^{T'}$ of locations $l_i^{T'}$ computed using them among the set L^T.

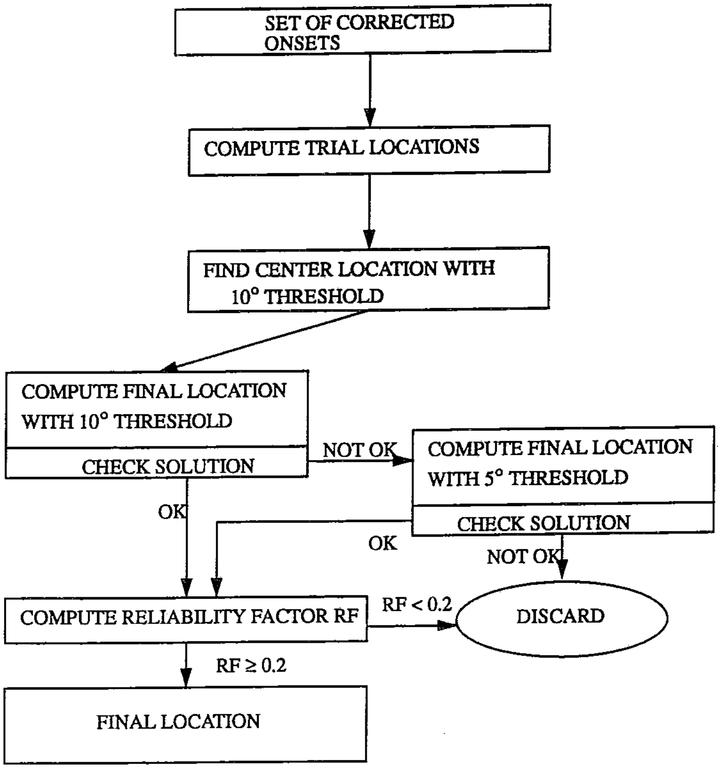

Fig. 2. Block diagram of automatic locator. The process is repeated independently using data filtered with each filtering band.

The next step is to compute the final location l^F from the set L^T of trial locations of various nature. Some of the locations in L^T are completely wrong solutions, whereas others reflect more or less the actual epicenter. If the data contains a clear teleseismic event, those trial locations in L^T, which were computed with real P-wave arrival times, i.e. $L^{T'}$, form a concentration around the epicenter. This is tested by going through all trial locations in L^T and counting number of other trial locations l_i^T, which lie closer than 10°. The l_i^T, which gets largest amount of counts, is chosen to be the center location l^C. The final location l^F is average of the center location and its neighbours closer than 10°.

Lat^F and lon^F are coordinates of the final location l^F. N_{10} is the number of trial locations l_i^T within 10° from the center location l^C, and lat_k and lon_k are their coordinates. Consequently lat^C and lon^C are coordinates of the center location l^C.

$$l^F = (lat^F, lon^F)$$

$$lat^F = \frac{1}{N_{10}+1}\left(\sum_{k=1}^{N_{10}} lat_k + lat^c\right) \qquad (2)$$

$$lon^F = \frac{1}{N_{10}+1}\left(\sum_{k=1}^{N_{10}} lon_k + lon^c\right)$$

All locations computed during the procedure for an earthquake in Japan (Aug. 14. 1993) are shown in Figure 3. The solution is tested by computing average residual R of P-wave arrival times. Also the number of trial locations $N = N_{10} + 1$ used to form the final location describes the reliability of the result. The logical rules for accepting the solution are

$$((N>10) and (R>1.5)) or ((N>20) and (R<2.0)) \qquad (3)$$

If obtained result does not satisfy the thresholds for acceptance, the procedure is repeated using the same center location and maximum distance of 5° for the epicenter related trial locations. If a satisfactory result is not found the detection is discarded.

As mentioned in the previous chapter the location procedure is repeated with onset times obtained with each filtering band separately. Thus it is possible to get 7 different locations. The best location result is chosen according to reliability factor RF, which gets high values when average residual R is small and number of accepted trial locations N is high.

$$RF = \frac{(B-4)}{(S-4)} - \frac{R}{2.1} \qquad (4)$$

S is number of stations in the system. The constant 2.1 is used only to set the proportional importance of the two terms in equation (4). B is derived from number of locations N.

$$B = (b-1) + \frac{N-N_{b-1}}{N_b-N_{b-1}} \qquad (5)$$

The minimum number of stations needed to form at least N tripartite subarrays is denoted with b. N_b is maximum number of tripartite subarrays that can be formed with b stations and accordingly N_{b-1} is maximum for $b-1$ stations. So formation of B maps number of accepted locations to another scale, which has number of stations as its unity. When average residual R is zero and all possible tripartite subarrays have been used to compute the final location, the reliability factor *RF* gets its maximum value 1. A low value implies incorrect location. The location with the highest *RF* value becomes the final solution. Example of the system output is shown in Table 2.

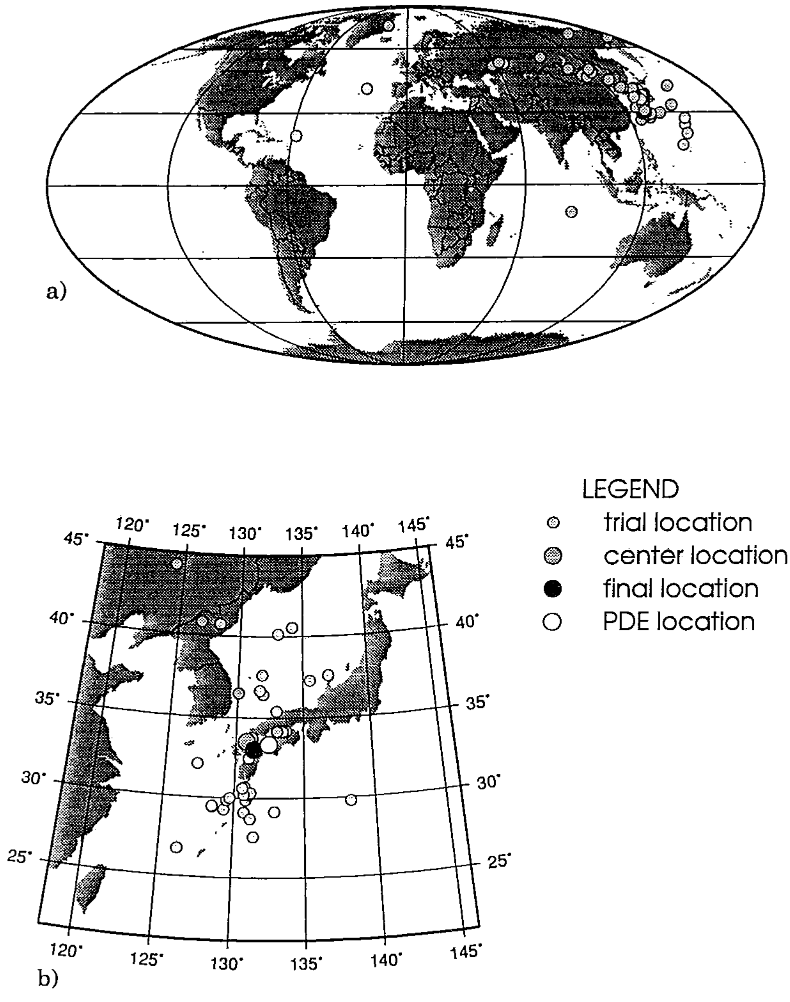

Fig. 3. (a) Trial locations of a teleseismic event are marked on the map. The noise and coda detections among onsets used to compute locations cause some totally erroneous solutions. A clear concentration of trial locations is seen in Japan region. The stretch of trials close to same backazimuth but with varying distance is caused by coda detections. (b) In the detailed map of the region also the center location, the final location and the PDE location are marked. The final location lies only 104.6 km from the PDE epicenter although the trial locations are scattered on a large area. The PDE information for the event: origin time 1993 08 14 01:29:17.7, lat 33.353°N, lon 132.436°E and mb 5.1.

Table 2. Automatic bulletin listing of 2 events. The PDE information for the first event: lat 23.157°N, lon 94.778°E and mb 4.3. The PDE information for the second even: lat 31.624°N, lon 49.901°E and mb 4.3. The last column in station table shows number of accepted trial locations, that were computed using the station.

USED 53/182 LOCATIONS, AVERAGE RESID: 0.09, RELIABILITY: 0.92 (max=1.0)
ORIGIN TIME: 1993001 23:49:28.9 Jan 1
LAT: 21.67 LON: 94.77 MB: 5.19 DEPTH SET TO: 10km
BURMA

sta	ch	time	qual	phase	A	T	dist	mb	az	baz	resid	used
KEF	sz	23:59:49.1	e	P	5.88	0.25	61.6	5.3	97.2	330.1	-0.0	20
SUF	sz	23:59:45.5	e	P	3.72	0.25	61.1	5.1	98.7	330.8	-0.2	20
KAF	sz	23:59:44.6	e	P	1.48	0.25	60.9	4.7	98.5	330.1	0.0	21
PVF	sz	23:59:44.6	i	P	8.88	0.30	60.9	5.4	97.2	328.3	0.0	20
PKK	sz	23:59:48.8	e	P	11.45	0.35	61.5	5.5	95.7	327.6	0.1	18
NUR	sz	23:59:48.6	e	P	2.83	0.30	61.5	4.9	96.1	328.2	0.0	19
VAF	sz	23:59:56.7	e	P	18.20	0.61	62.7	5.4	95.6	331.0	0.2	21
JOF	sz	23:59:30.0	i	P	8.29	0.28	58.8	5.3	103.6	331.6	-0.1	20

USED 29/35 LOCATIONS, AVERAGE RESID: 0.18, RELIABILITY: 0.57 (max=1.0)
ORIGIN TIME: 1993002 03:42:30.5 Jan 2
LAT: 30.68 LON: 49.20 MB: 4.58 DEPTH SET TO: 10km
WESTERN IRAN

sta	ch	time	qual	phase	A	T	dist	mb	az	baz	resid	used
KEF	sz	03:49:26.7	e	P	2.09	0.30	35.2	4.5	142.1	340.5	0.2	13
SUF	sz	03:49:27.1	e	P	2.28	0.30	35.3	4.6	144.3	341.9	-0.1	12
KAF	sz	03:49:22.6	e	P	1.86	0.30	34.8	4.5	144.1	341.4	-0.1	12
PVF	sz	03:49:13.2	e	P	3.60	0.35	33.6	4.7	142.0	339.4	0.1	14
NUR	sz	03:49:16.1	e	P	1.21	0.30	34.0	4.3	140.3	338.5	0.1	13
VAF	sz	03:49:37.8	i	P	1.48	0.22	36.5	4.4	139.8	340.1	0.1	14
JOF	sz	03:49:17.6	e	P	9.39	0.36	34.2	5.1	152.0	345.6	-0.4	9

5. *Performance results and discussion*

The system has been operating with 8 stations since December 1 1991. During the operation there has been periods when one or more of the stations has been disabled to produce data mostly due to data transmission problems. In order to get a reliable and comparable picture of the capabilities of the system, only those days on which all stations had been operating in December 1991 and 1992 were selected. This resulted 317 days. Automatic bulletin was compared to Preliminary Determination of Epicenter (PDE) bulletins of National Earthquake Information Center (NEIC). Number of automatically located events found in PDE list was 857. The thresholds for accepting the events were 90 second difference in origin time and 2500 km difference in epicenter location. The distance and mb distributions of these events are shown in Figure 4.

An important aspect closely related to performance capabilities of the system is setting the threshold limit for *RF* to weed out false locations from the automatic bulletin. Their is an obvious trade-off between number of false locations accepted in the bulletin and good quality solutions which are left out. So the threshold has to be selected carefully. Also the accuracy of locations has to be considered. The percential amount of automatic locations connected to events in PDE lists for different *RF* ranges is presented in Figure

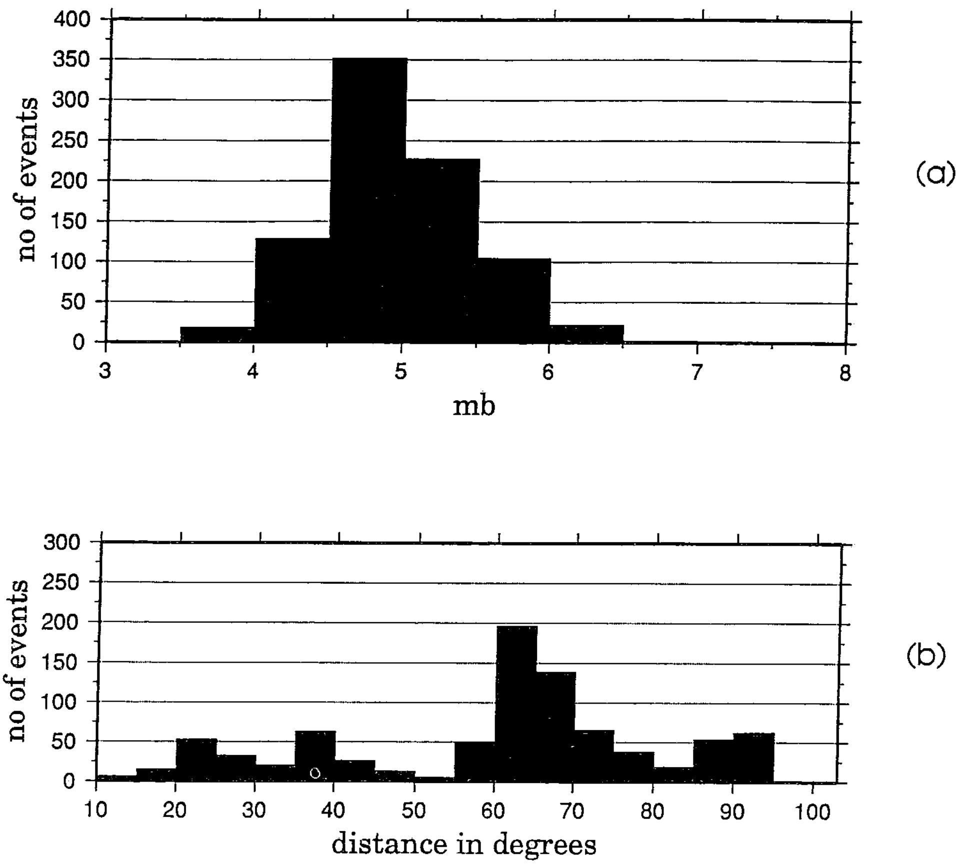

Fig. 4. Distribution of mb (a) and distance (b) of events found both in automatic bulletin and PDE bulletin.

5. The PDE lists are not final bulletins so they do not include all events. Consequently percentages in Figure 5 give only an approximation of the error rate of the automatic bulletin. The percentages would be higher if comparison could be made with, for example, International Seismological Center (ISC) catalogue, which were not yet available for the time period. The distribution of location difference compared to PDE bulletin is shown in Figure 6a. Most of the differences are relatively small. The median of location difference is 328.6 km. The slowness and azimuth anomalies in northern Europe reported in several articles can cause location errors close to this or even larger (*Brown*, 1973, *Noponen*, 1974, *Berteussen*, 1976), up to 1sec/deg and 7°, depending on the number of stations and aperture of the station network. When a large network covering the whole Fennoscandia has been used, the observed slowness and azimuth anomalies have been much smaller (*Husebye et al.* 1971). In Figure 6b the location difference is plotted as a function of *RF*. Most of the

events with high *RF* value have small difference in locations. With small *RF* values location differences grow larger and they are strongly scattered. Because large variance prevents forming a good picture of the relation between *RF* and the location difference a polynomial curve is fitted to the data. The solid line in Figure 6b is a polynomial regression model with 4 terms fitted to data set by least squares method. The threshold limit for *RF* should not constrain number of events too much since a significant amount of events found in PDE list had rather low *RF* value. On the other hand large amount of false locations has to be cut down. The limit was set empirically to 0.2. At this point the fitted curve in Figure 6b reaches 600 km level in location difference. It is also minimum level for finding 50 % or more of events in automatic bulletin from PDE bulletin (see Figure 5). With this threshold level the system located 55 % of events with mb>5.5 in PDE bulletin, 36 % with 5.5>mb>5.0 and 21 % with 5.0>mb>4.5. These results depend also on operational characteristics of the detector system. With slightly different filtering bands the detector system has been reported to detect 33 % of all the events in PDE bulletin with similar daily detection rate (*Tiira*, 1989). Deeper inspection of this issue is beyond the scope of this article.

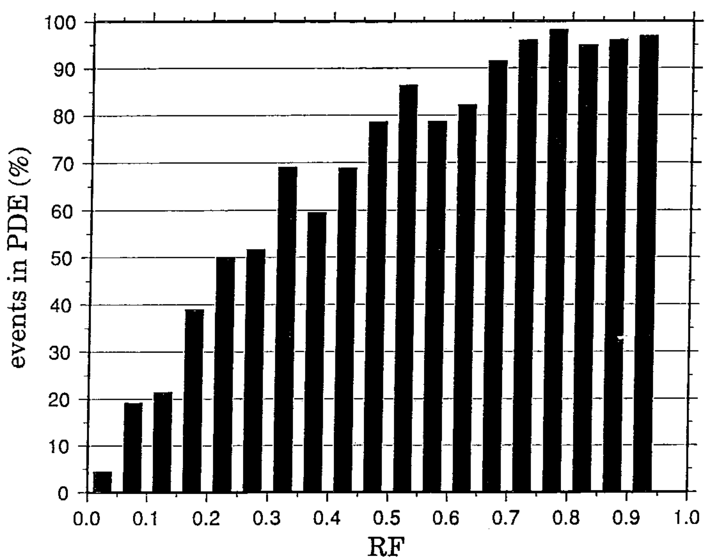

Fig. 5. The percential amount of automatic locations connected to event in PDE list for different RF ranges.

The median of location error for events with $RF \geq 0.2$ was 297.0 km. *Shapira* and *Båth* (1976) reported 1.4° (155 km) average distance difference with ISC bulletins when they used 6 Swedish stations to locate 26 manually analysed teleseismic events. *Ruud* (1990) applied three different location methods, fitting a plane wavefront to the arrival

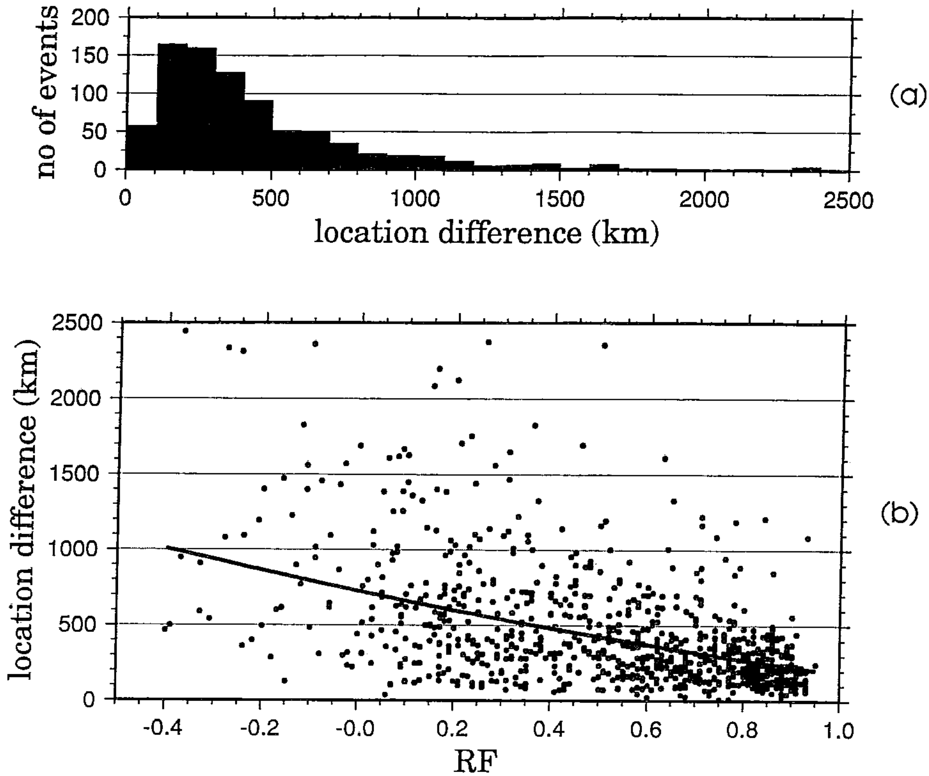

Fig. 6. (a) The distribution of location difference between automatic bulletin and PDE bulletin. (b) The location differences as a function of RF. The solid curve represents polynomial model with 4 terms fitted to the data.

times, fitting a curved wavefront based on Taylor expansion and fitting arrival times directly to traveltime tables on data from 10 Swedish and Finnish stations. The average location errors of 10 selected events from ISC bulletins for each method were 701 km, 155 km and 133 km correspondingly. When these results are compared with automatic method one must keep in mind that they were obtained with small number of manually analysed events. So, greater accuracy was expected. *Tarvainen* and *Heikkinen* (1993) have made a study presenting correction factors for slowness vector to counter effects of slowness anomalies mainly due to geological structure near the station. They found that median location error of 667 associated teleseismic events for a tripartite array with stations KEF, SUF and KAF dropped from 639 km to 173 km by using correction factors. The original locations showed also distinct regional behaviour in azimuth and size of location differences. The method used in automatic locator reduces error induced by local structural slowness vector anomalies by averaging results of several tripartite arrays. The averaging reduces also errors caused by inaccuracy in onset time estimation. Error due to regional slowness anomalies remains in the results. Another source of error is large aperture of some of the tripartite arrays used in this study. Maximum distance between 2 stations is 412 km (from JOF to VAF). The location routine approximates incoming wavefront with plane wave and this causes error in slowness vector when distances between stations grow larger. On the other hand using large network reduces effects of near station structures. Fourth source of error is that depth of an event is not taken into account in this study. The location differences are shown in Figure 7. The picture shows that there is no strong systematic behaviour that would imply effects of slowness anomalies near the stations.

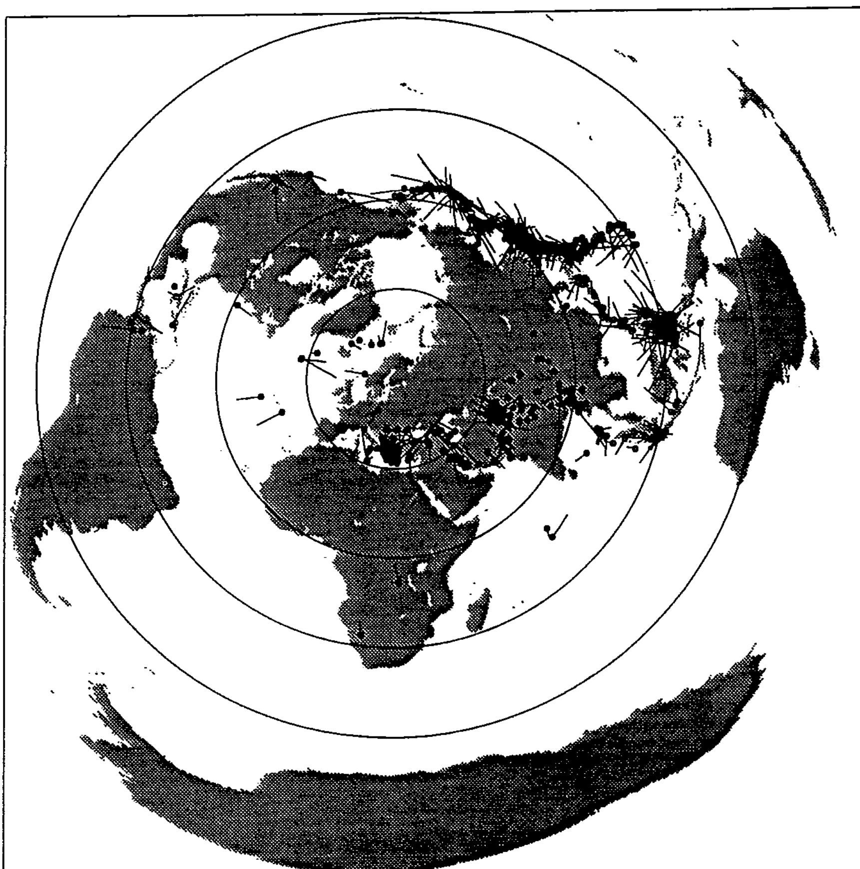

Fig. 7. Location errors of associated events. Point of arrow shows PDE location of the event.

Comparing automatic bulletin with PDE bulletins and results of routine analysis done by experienced analysts revealed that 350 of the automatically located events were not among the 727 manually located events and the automatic bulletin lacked 226 events that were manually located. The detection list used as a starting point and the available data were same for both processes.

Several methods have been developed for earthquake location, which fit all possible data at the same time to some wavefront model (*Geiger*, 1910, *Bolt*, 1960, *Buland*, 1976, *Thurber*, 1985, *Ruud*, 1990). The method used here was developed particularly for automatic location of teleseismic events with local network. The use of several subarrays and averaging the results utilizes the same information as simultaneous wavefront fitting of all arrivals, but it gives some advantages for automatic processing. It is not essential to preselect the real onsets from all detections, but the location procedure does the selection. Erroneous onsets will be weeded out. Resembling trial and error based selection with some conventional method would be very inefficient, since the waveplane fitting is done here only to 3 onsets at the time, which is faster than using all stations in each trial. Also the number of possible trial locations is smaller, especially when number of onsets is large. The method incorporates a weighting system for onsets. Good quality onsets are used more often in accepted trial locations than those with higher residuals. Iterative computation for finding optimal weights is not needed.

6. *Conclusions*

The aim of this work was to create a simple automatic location method for teleseismic events. The system developed for this purpose has been in use about 3 years. The latest configuration has proven to be able to locate teleseismic events with considerable accuracy for an automatic system bearing in mind, that requirements for station network are very modest and that the system is fully automatic. The system can be used with very simple network. 5 single channel z-component short period stations are enough for running the system. In theory 4 station were enough for running the system but in practice at least 5 stations are needed to give enough 3 station locations to lower effects of onset time errors.

The exactness of the results is better than those of manual analysis of one tripartite array would be without slowness anomaly corrections. The effects of local slowness anomalies are cancelled when locations of several tripartite arrays are averaged. Similarly inaccuracy in automatic onset measurements is compensated. The usage of several stations favours also the automatic system in this comparison. The smaller the array is the more sensitive it is to slowness anomalies caused buy lateral inhomogenities in the mantle (*Davies* and *Sheppard* 1972, *Gjøystdal et al.* 1973). The location error is mainly contributed to two aspects, the remaining effects of slowness vector anomalies and inaccuracy in automatic onset picking. Systems with larger aperture networks or slowness correction and manual onset picking produce only about 50 % smaller average error than the fully automatic system. The location accuracy was not strongly dependent on distance or magnitude of the event.

The system is capable of locating small events, even with mb below 4.0. Half of the located events during 13 month test period had mb≤4.8. Possible false alarms are discarded from automatic bulletin using a reliability factor computed from system output. 80 % of the events above acceptance level were found in PDE bulletin. This does not mean that all other events would be false alarms because PDE bulletins do not include all events with mb magnitude above 3.5.

The processing of events done by automatic locator differs from decision making of an human analyst. An analyst recognizes an event by comparing seismograms from several stations and connecting possible onsets and shapes of wavelets in different stations. The decision process applies also pattern recognition with knowledge of what events usually look like, generated by learning and experience. An experienced analyst has created large memorized "data set" into which new events are compared. The automatic locator does not compete with human analyst in this area, but it has one benefit due to its robust way to approach the problem. If onsets are weak and corresponding wavelets differ from each other in different stations it is difficult to distinguish an event from a false alarm. An analyst will not try to locate the event, or may even disregard the detection, which is the right decision in case of a false alarm. If, however, an event is present it is left unanalyzed. The automatic locator tries to locate even the unlikely events. Even very weak events may be located since precision of onset times is not crucial in this method. This explains the fact that automatic locator located more events than were manually located. Several improvements would enhance the performance of the system. Automatic recognition of first arrivals, more accurate onset picking method and utilizing 3-component data are just a few. In the current system all detections are processed by the locator. This causes some false alarms because local events with large amount of coda detections may produce sets of onsets which give acceptable solutions for teleseismic epicenter locations. The problem could be avoided by using some statistical method or artificial neural net based system to select possible teleseismic events from all detections.

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References

Bache, T.C., Bratt, S.R., Wang, J., Fung, R.M., Kobryn, C. and Given, J.W. 1990: The intelligent monitoring system. *Bull. Seism. Soc. Am.* **80**, 1833-1851.

Berteussen, K.A., 1974: NORSAR location calibrations and time delay corrections. *NORSAR Sci. Rep.* No. **2-73/74**, Kjeller, Norway, 37 pp.

Berteussen, K.A., 1976: The origin of slowness and azimuth anomalies at large arrays. *Bull. Seism. Soc. Am.* **66**, 719-741.

Bolt, B.A., 1960: The revision of earthquake epicentres, focal depths and origin-times using a high-speed computer. *Geophys. J. R. astr. Soc.* **3**, 433-440.

Brown, R.J., 1973: Slowness and azimuth at the Uppsala Array. *Pure and Appl. Geophys.* **109**, 1623-1637.

Buland, R., 1976: The mechanics of locating earthquakes. *Bull. Seism. Soc. Am.* **66**, 173-187.

Davies, D. and Sheppard, R.M., 1972: Lateral heterogeneity in the Earth's mantle. *Nature* **239**, 318-323.

Geiger, L., 1910: Herdbestimmung bei Erdbeben aus den Ankunftzeiten. *K. Gessell. Goett.* **4**, 331-349.

Gjøystdal, H; Husebye, E.S. and Rieber-Mohn, D. 1973: One-array and two-array location capabilities. *Bull. Seism. Soc. Am.* **63**, 549-569.

Greenfield, R.J. and Sheppard, R.M., 1969: The moho depth variations under the LASA and their effect on $dT/d\Delta$ measurements. *Bull. Seism. Soc. Am.* **80**, 409-420.

Harris, D.B., 1990: Comparison of the direction estimation performance of high-frequency seismic arrays and three-component stations. *Bull. Seism. Soc. Am.* **80**, 1951-1968.

Husebye, E.S., Kanestrøm, R. and Rud, R.,1971: Observations of vertical and lateral P-velocity anomalies in the Earth's mantle using the Fennoscandian continental array. *Geophys. J. R. astr. Soc.* **25**, 3-16.

Kedrov, O.K. and Ovtchinnikov, V.M., 1990: An on-line analysis system for three-component seismic data: method and preliminary results. *Bull. Seism. Soc. Am.* **80**, 2053-2071.

Kulhànek, O., 1990: Anatomy of Seismograms. *Elsevier Science Publishers* B. V., Amsterdam.

Murdock, J.N. and Halbert, S.E., 1987: A C language implementation of the SRO (Murdock) Detector/Analyzer. *U.S. Geol. Survey Open File rept.* 87-158.

Murdock, J.N. and Hutt, C.R., 1983: A new event detector designed for the Seismic Research Observatories. *U.S. Geol. Survey Open File rept.* 83-785.

Mykkeltveit, S., Ringdal, F., Kværna, T. and Alewine, R.W., 1990: Application of regional arrays in seismic verification research. *Bull. Seism. Soc. Am.* **80**, 1777-1800.

Noponen, I., 1974: Seismic ray direction anomalies caused by deep structure in Fennoscandia. *Bull. Seism. Soc. Am.* **64**, 1-11.

Pisarenko, V.F., Kushnir, A.F. and Savin, I.V., 1987: Statistical adaptive algorithms for estimation of onset moments of seismic phases. *Phys. Earth Planet. Inter.* **47**, 4-10.

Roberts, R.G., Christofferson, A. and Cassidy, F., 1989: Real-time event detection, phase identification and source location estimation using single three-component seismic data. *Geophys. J.* **97**, 471-480.

Ruud, B.O., 1990: Teleseismic epicentre locations from arrival times at regional networks. *Geophys. J. Int.* **100**, 515-519.

Ruud, B.O. and Husebye E. S., 1992: A new three-component detector and automatic single-station bulletin production. *Bull. Seism. Soc. Am.* **82**, 221-237.

Shapira, A. and Båth, M., 1976: Location of teleseisms from P-wave arrival at the Swedish stations. Report No. 9-76, Seismological Institute, Uppsala, 21 pp.

Suteau-Henson, A., 1990: Estimating azimuth and slowness from three-component and array stations. *Bull. Seism. Soc. Am.* **80**, 1987-1998.

Tarvainen, M., 1991: Detecting local and regional seismic events using the data- adaptive method at the VAF seismograph station in Finland. *Bull. Seism. Soc. Am.* **81**, 1373-1379.

Tarvainen, M. and Heikkinen, P., 1993: Correcting of location of teleseismic events obtained from recordings at FINET seismic stations in Finland. *Geophysica* **28**, 1-14.

Tiira, T., 1989: Seismisten signaalien havaitseminen Hutt&Murdock-detektorin ja digitaalisen suodatuksen avulla. M.Sc. thesis, University of Helsinki, Institute of Physics, 75 pp, (in Finnish).

Thurber, C.H., 1985: Nonlinear earthquake location: Theory and examples. *Bull. Seism. Soc. Am.* **75**, 779-790.