The Research Council of Norway (NFR)

NORSAR

NORSAR Scientific Report No. 1-93/94

Semiannual Technical Summary

1 April — 30 September 1993

Kjeller, November 1993

APPROVED FOR PUBLIC RELEASE, DISTRIBUTION UNLIMITED

7.4 A generic algorithm for accurate determination of P-phase arrival times

Introduction

A precise estimate of the onset time of seismic phases is needed to obtain an accurate event location. To obtain very precise onset times for all types of seismic signals, seismological observatories around the world mostly rely on the picks provided by their human analysts. However, the increase in the number of seismic stations worldwide has not been followed up by a similar increase in the number of analysts. The availability and operational use of reliable, automatic procedures therefore become more and more important.

In the automatic detection and signal processing module (SigPro) used for processing the regional array data at NORSAR, a two-step onset time algorithm is in use. This procedure consists of first applying a series of short-term to long-term average (STA/LTA) detectors in parallel to a set of filtered beams. When one or more of the STA/LTA detectors exceed a predefined threshold, a phase detection is declared and a detection time is found. Subsequently, a time domain phase timing algorithm is applied to the filtered beam with the highest SNR, using the detection time as the starting value. A detailed description of this algorithm is found in Mykkeltveit and Bungum (1984).

These SigPro estimates of the onset times are subsequently used by the automatic phase association and event location procedure (ESAL) of the Intelligent Monitoring System (IMS) (Bache et al, 1993) to produce a fully automatic event bulletin. The IMS currently provides for joint processing of data from six arrays located in northern and central Europe, see Fig. 7.4.1. The events in the automatic bulletin are finally reviewed and corrected by the analyst using the Analyst Review Station (ARS) of the IMS. Through the analyst review we have experienced that the phase onset times often have to be significantly adjusted. In order to improve the precision of the automatic event locations provided by the IMS and in order to reduce the analyst's workload, there is therefore a strong need to improve the precision of the automatic onset time estimates.

Autoregressive modelling has been shown to provide a useful tool in characterizing seismic noise and signals. Tjøstheim (1975a,b) applied such modelling to the seismic discrimination problem. Takanami (1991) used autoregressive models for onset time estimation for microearthquake networks. Pisarenko et al (1987) developed a general autoregressive onset time estimator, which was further elaborated by Kushnir et al (1990). In this study we will investigate the use and performance of this onset time estimation method when applied in an automatic mode under various types of conditions.

In this paper, we develop a generic procedure to reestimate the onsets of all types of first-arriving P-phases using the SigPro onset estimates as a starting point. By applying the autoregressive likelihood technique, we have obtained automatic onset times of a quality such that 70% of the automatic picks are within 0.1 s of the best manual pick. For the SigPro onset time procedure currently used at NORSAR, the corresponding number is 28%. We conclude that automatic reestimation of first-arriving P-onsets using the autoregressive likelihood technique has the potential of significantly reducing the retiming efforts of the analyst.

Autoregressive likelihood estimation of onset time

Following Pisarenko et al (1987) and Kushnir et al (1990), the autoregressive likelihood algorithm for onset time estimation is based on regarding the signal onset as the time when the statistical features of the observed time series are abruptly changed. For each argument τ within a predefined search interval (t_1, t_2) of length N, autoregressive models of the observations within the intervals (t_1, τ) and (τ, t_2) are calculated by a Levinson-Durbin procedure. From the variances σ_1^2 and σ_2^2 of the autoregressive model residuals of the two time intervals, a maximum-likelihood algorithm is used to calculate the likelihood function $L(\tau)$ in accordance with the formula

$$L(\tau) = [\tau ln\sigma_1(\tau) - (N-\tau) ln\sigma_2(\tau)] \quad (1)$$

where the argument to the maximum of $L(\tau)$ defines the onset time of the signal, see Fig. 7.4.2.

The algorithm working on single component data, hereafter denoted ESTON1, takes into account changes in both power and frequency content, and it is therefore important that the broadband signal waveforms are retained. This is very different from the onset time estimator currently used in SigPro, which only exploits power differences within the narrow frequency band with the highest signal-to-noise ratio (SNR). The algorithm working on three component data, hereafter denoted ESTON3, is in addition sensitive to changes in the polarization characteristics of the three-component observations. Following the recommendations of Pisarenko et al (1987), we have in all our calculations used autoregressive modelling of order 3.

It is noteworthy that both ESTON1 and ESTON3 require that the search be limited to a relatively short time window. If an initial event location and origin time is known, we can determine the required short time window for the search. Alternatively, the phase onsets provided by SigPro can be used to restrict the search. In any case, the autoregressive likelihood estimation of onset time should be well-suited to a post-processing application.

Generic application; retiming of first-arriving P-phases

We have conducted an experiment in reestimating the onset time of all first-arriving P-phases defined in the automatic IMS bulletin, using the ESTON1 method. For a period of four days (September 27 - 30, 1993), 391 first-arriving P-phases associated with events in the IMS bulletin were defined. They were distributed among all the arrays shown in Fig. 7.4. 1, and originated from events at both local, regional and teleseismic distances. All P-phases were carefully retimed using an interactive signal processing package (EP) with high-resolution graphics (Fyen, 1989), and about 10% of them were rejected due to false detections or erroneous phase association, such that 350 first-arriving P-phases remained for further analysis after this manual screening process. When comparing these numbers to the general IMS performance (Mykkeltveit et al, 1993), it appears that this sample is fairly typical for an operational situation.

The 149 P-phases recorded during the two first days of the time period were used to tune the implementation of ESTON1. By comparing the differences between the manual and the SigPro onset times, a maximum difference of 2.8 s was observed. Consequently, the search interval to be used by ESTON1 was set to ±3 s around the SigPro onset.

The different types of P-phases (Pg, Pn, P and PKP) spanned a wide range of signal characteristics with respect to spectral content, complexity, SNR and signature (impulsive, emergent). From extensive testing of ESTON1, we found that in order to successfully process all types of signals, we had to identify the widest possible spectral band for which the signal had usable SNR. This was done in the time domain by estimating the maximum SNR within the search interval in a series of narrow passbands. The spectral band was defined such that we initially selected the narrow frequency band with the highest SNR. If the neighboring frequency bands had an SNR within a factor of 5 of the maximum and also exceeded an SNR of 4, the spectral band was extended so as to include this band as well.

Our experiments also showed that in order to obtain stable estimates of the likelihood function $L(\tau)$, it was important to filter and decimate the data in accordance with the highest frequency of the signal spectrum. For signals with a high SNR (typically above 40) and a wide bandwidth, no filtering or decimation was needed.

We found that the onsets provided by ESTON1 were biased slightly late, and the delay appeared to be linearly dependent on the dominant period of the signal. By linear regression of all signals with SNR > 6, the bias b could be approximated by the relation $b \approx 0.38p$ where p is the dominant period of the signal. The flowchart of Fig. 7.4.3 outlines the processing steps involved in the reestimation of the arrival time of first-arriving P-phases using the ESTON1 method.

The 201 P-phases recorded during the last two days of the test period were used to evaluate the new procedure. Fig. 7.4.4a shows the difference between the manually picked onsets and the automatic onsets from SigPro versus the highest SNR measured in any narrow filter band. For comparison, Fig. 7.4.4b shows the difference between the manually picked onsets and the automatically reestimated onset times using the ESTON1 method. From comparing these two figures it is apparent that the improvement when using ESTON1 is significant for all SNRs.

To quantify the improvement, we have in Fig. 7.4.5 plotted the percentage of the observations within a range of absolute time differences between the automatic and the manual picks. For SigPro, 50 percent of the automatic onsets were within 0.23 s of the manual pick, whereas for ESTON1 the 50 percent level (median) was as low as 0.05 s.

We also divided the observations into a teleseismic and a local/regional data set. For SigPro, the median time differences were about equal for the two data sets. For ESTON1, the median time difference was slightly smaller for the local/regional data set than for the teleseismic. This difference could be due to generally longer dominant periods of the teleseismic P-phases.

As expected and also seen from Figs. 7.4.4a and 7.4.4b, the precision of the automatic onsets is best for high SNRs. By again dividing the observations into two data sets, one with SNR less than or equal to 10 and one with SNR greater than 10, we found that SigPro had a median difference of 0.29 s for the low SNR data set and 0.19 s for the other. The corresponding numbers for ESTON1 were 0.10 s and 0.04 s, respectively.

The implications on the analyst's retiming efforts can be illustrated by the following example: If we assume that the analyst will accept a maximum deviation of 0.1 s from the "correct" manual pick without doing retiming, we can from Fig. 7.4.5 see that 28 percent of the SigPro onsets are acceptable, whereas 70 percent of the ESTON1 onsets are acceptable. Clearly, automatic reestimation of first-arriving P-onsets using the algorithm described above has the potential of significantly reducing the retiming efforts of the analyst.

Conclusions

The results presented in this study show that very precise automatic estimates of phase onsets can be obtained with the autoregressive likelihood estimation technique. Implementation of the method requires that we have available approximate estimates of the phase arrival, and we have shown that such approximate estimates can be obtained from automatic event definitions (phase association and event location) by the Intelligent Monitoring System (IMS). In this way the autoregressive likelihood estimation method can provide phase onsets that match the human precision. This has previously been demonstrated for events from the Khibiny Massif, by quantifying the uncertainty of both manual and automatic onset estimates of various phases at the Apatity stations and at ARCESS (Kværna, 1993). Furthermore, the precision of the automatic phase picks shows very large improvement in comparison to the automatic phase onsets from the continuous processing providing input to the IMS.

We realize that in order to obtain accurate event locations, precise onset time estimates are necessary, but not sufficient. If the theoretical travel-time model used in the event location deviates from the true travel-times, the accuracy of the event locations will be reduced. Introduction of travel-time corrections as well as other aspects of accurate event location are discussed by Kværna and Ringdal (1993).

During the work with the autoregressive likelihood estimation method, we have experienced that the display of the likelihood functions, as illustrated in Fig. 7.4.2 can assist the analyst in picking the correct phase onsets. In the context of interactive analysis of seismic data, we believe that the idea of making such likelihood functions available to the analyst should be pursued.

It is clear that when estimating arrival times by the autoregressive method, the results for specific, well-calibrated regions are more precise than can be obtained when the method is used in a "generic" mode. Efforts should be made to extend the number of well-calibrated regions in order to make such optimum use of the method.

T. Kværna

References

Bache, T.C., S.R. Bratt, H.J. Swanger, G.W. Beall and F.K. Dashiell (1993): Knowledge-based interpretation of seismic data in the Intelligent Monitoring System, *Bull. Seism. Soc. Am.,* 83, 1507-1526..

Fyen, J. (1989): Event processor program package, in *NORSAR Semiannual Tech. Summ. 1 Oct 1988 - 31 Mar 1989*, Scientific Rep. No.2-88/89, Kjeller, Norway.

Kushnir, A.F., V.M. Lapshin, V.I. Pinsky and J. Fyen (1990): Statistically optimal event detection using small array data, *Bull. Seism. Soc. Am.*, 80 Part B, 1934-1950

Kværna, T. (1993): Intelligent post-processing of seismic events -- Part 2: Accurate determination of phase arrival times using autoregressive likelihood estimation, in *NORSAR Semiannual Tech. Summ. 1 Oct 1992 - 31 Mar 1993*, Scientific Rep. No. 2-92/93, Kjeller, Norway.

Kværna, T. and F. Ringdal (1993): Intelligent post-processing of seismic events, submitted for publication.

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

Mykkeltveit, S., U. Baadshaug, B. Kr. Hokland, T. Kværna and L. B. Loughran (1993): An evaluation of the performance of the Intelligent Monitoring System, in *NORSAR Semiannual Tech. Summ. 1 Oct 1992 - 31 Mar 1993*, Scientific Rep. No.2-92/93, Kjeller, Norway.

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

Sereno, T.J. (1990): Attenuation of regional phases in Fennoscandia and estimates of arrival time and azimuth uncertainty using data recorded by regional arrays, *NORSAR Seminann. Tech. Rep. No. 3, 1 Jan 89 - 30 Jun 90,* Science Applications International Corp., San Diego, CA, USA.

Takanami, T., (1991): A study of detection and extraction methods for microearthquake waves by autoregressive models, *Journal of the Faculty of Science, Hokkaido University Series VII (Geophysics)*, Vol. 9, No. 1

Tjøstheim, D., (1975a): Some automatic models for short-period noise, *Bull. Seism. Soc. Am.*, 65, 677-691.

Tjøstheim, D., (1975b): Autoregressive representation of seismic P-wave signals with an application to the problem of short-period discriminants, *Geophys. J. Roy. Astron. Soc.*, 43, 269-291.

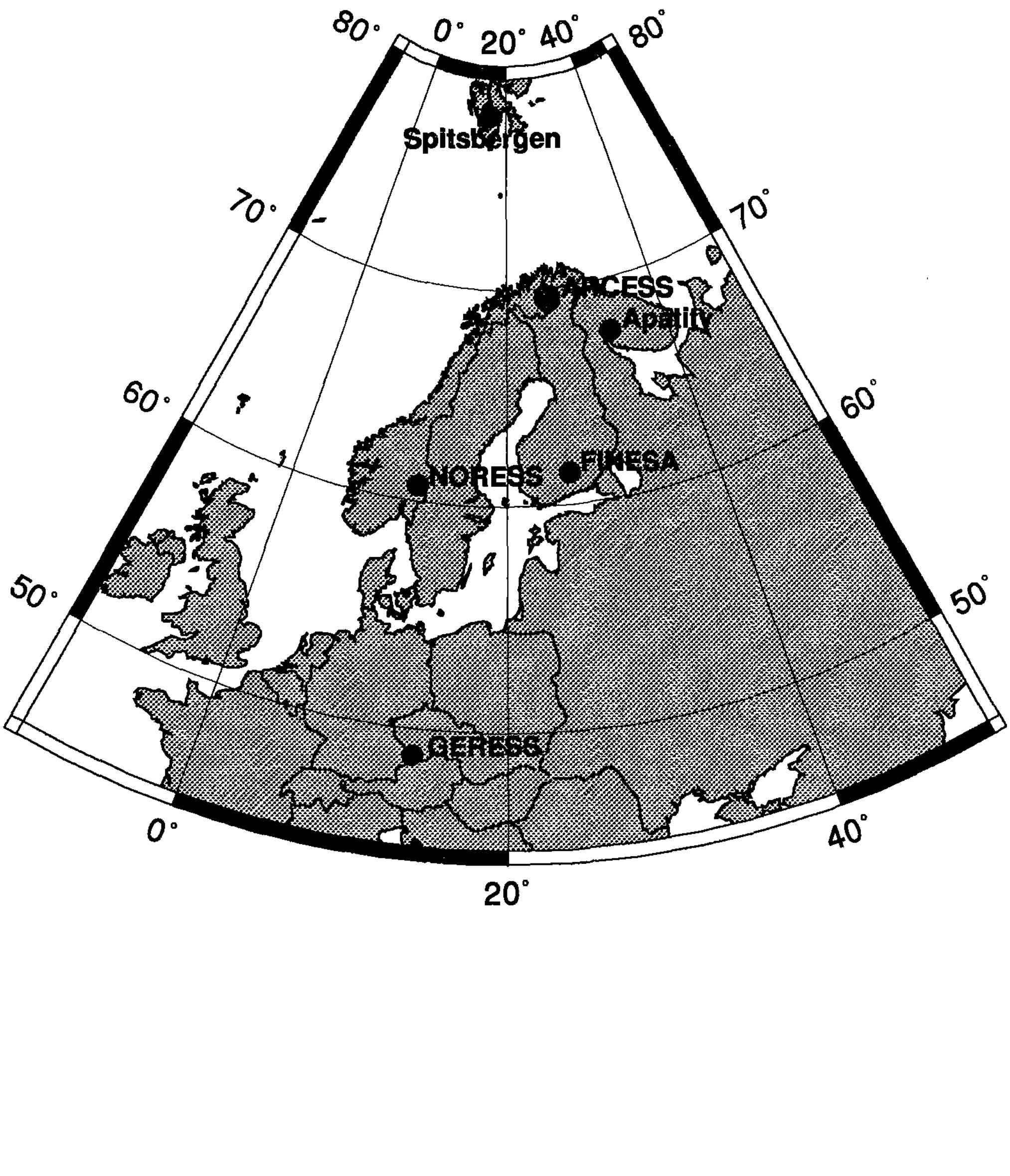


Fig. 7.4.1. Map showing the locations of the six regional arrays currently used by the Intelligent Monitoring System at the NORSAR data processing center.

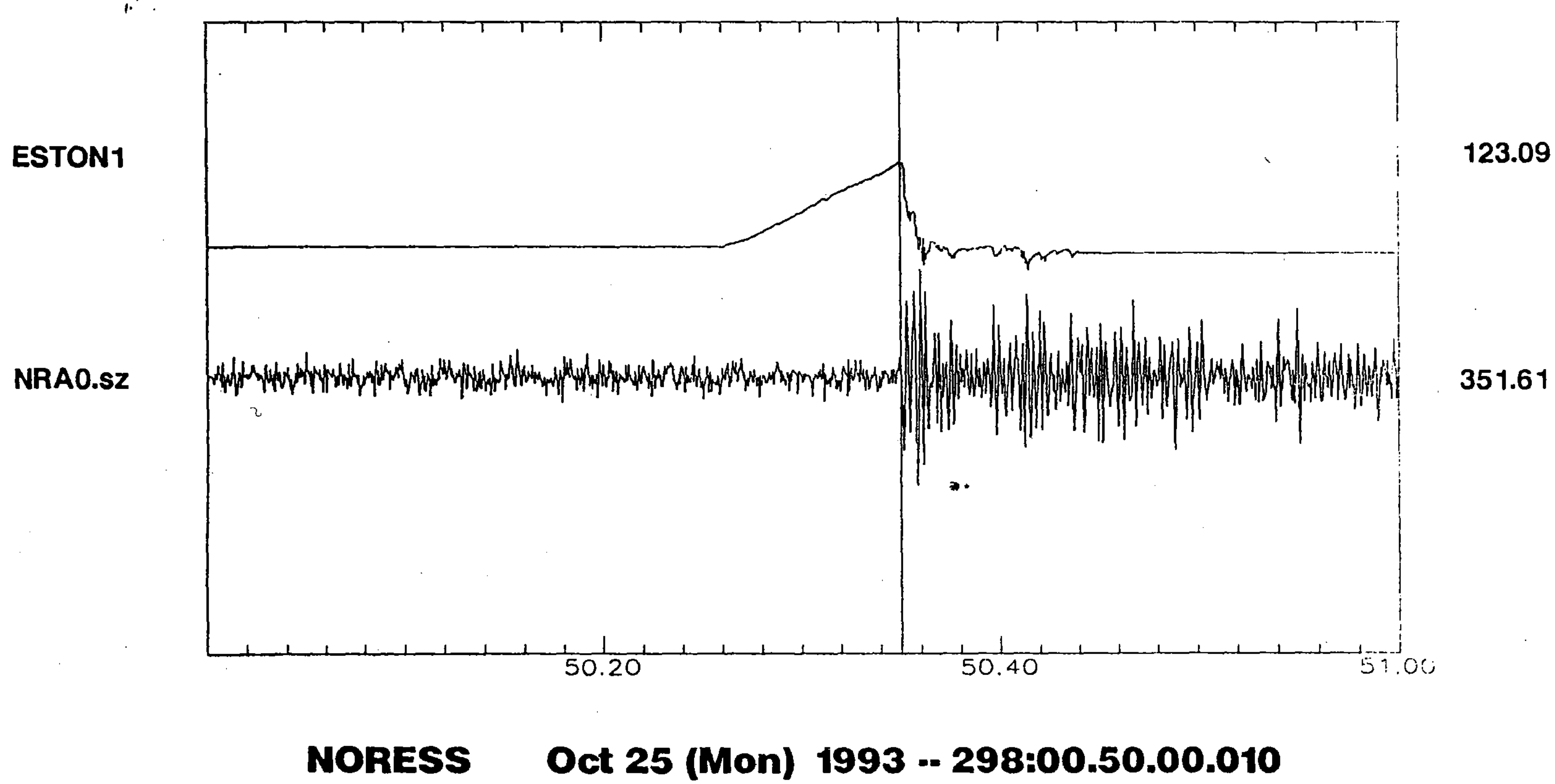


Fig. 7.4.2. The top trace is the likelihood function resulting from autoregressive onset time estimation of the data in the bottom trace. The maximum of the likelihood function corresponds to the estimated onset time.

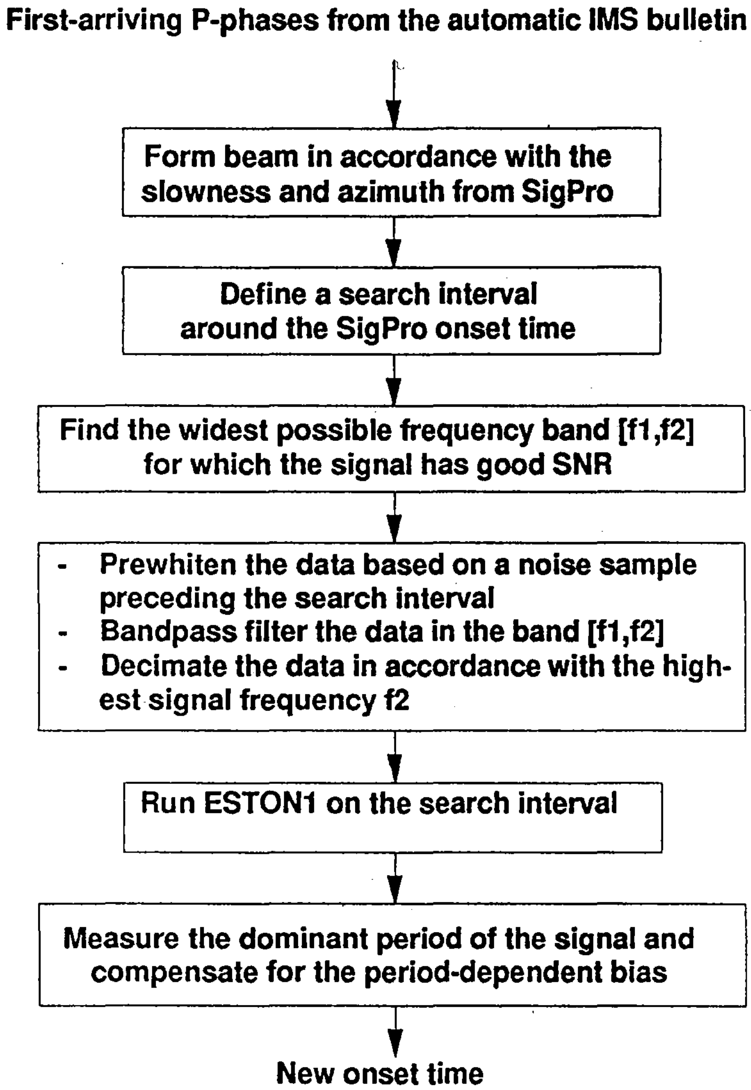
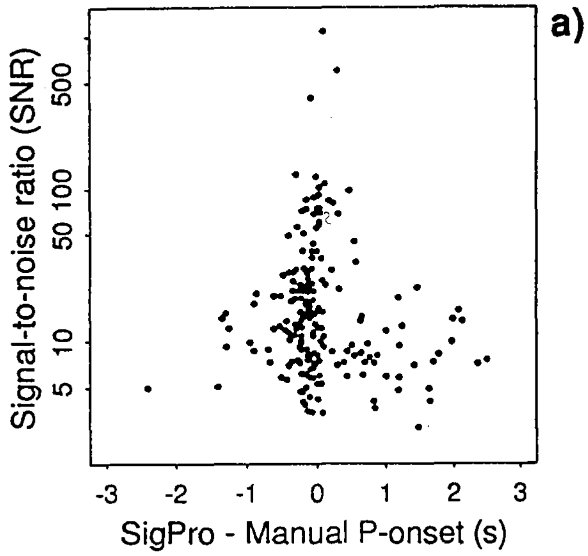


Fig. 7.4.3. Flowchart illustrating the processing steps involved in the reestimation of the arrival time of first-arriving P-phases using the ESTON1 method.



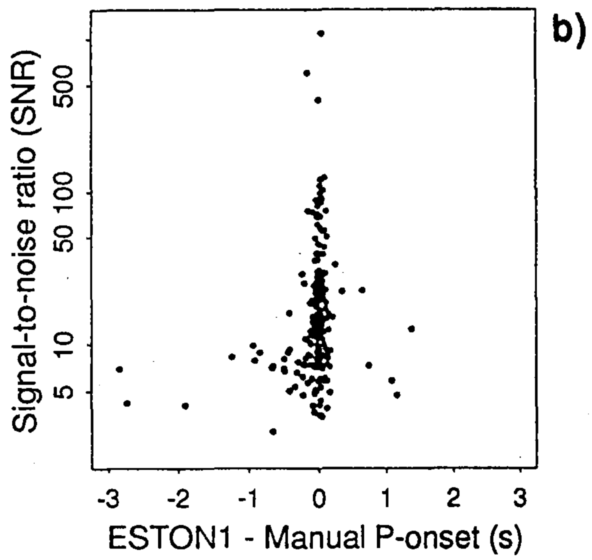


Fig. 7.4.4: This figure show the time difference between the automatic and the manually picked onsets of the 201 first-arriving P-phases analyzed in this study plotted versus the SNR of the signal.
a) shows the time differences between the automatic onsets from SigPro and the manual picks. The median absolute time difference is 0.23 s.
b) shows the time differences between the reestimated onsets from ESTON1 and the manual picks. The median absolute time difference is 0. 05 s.

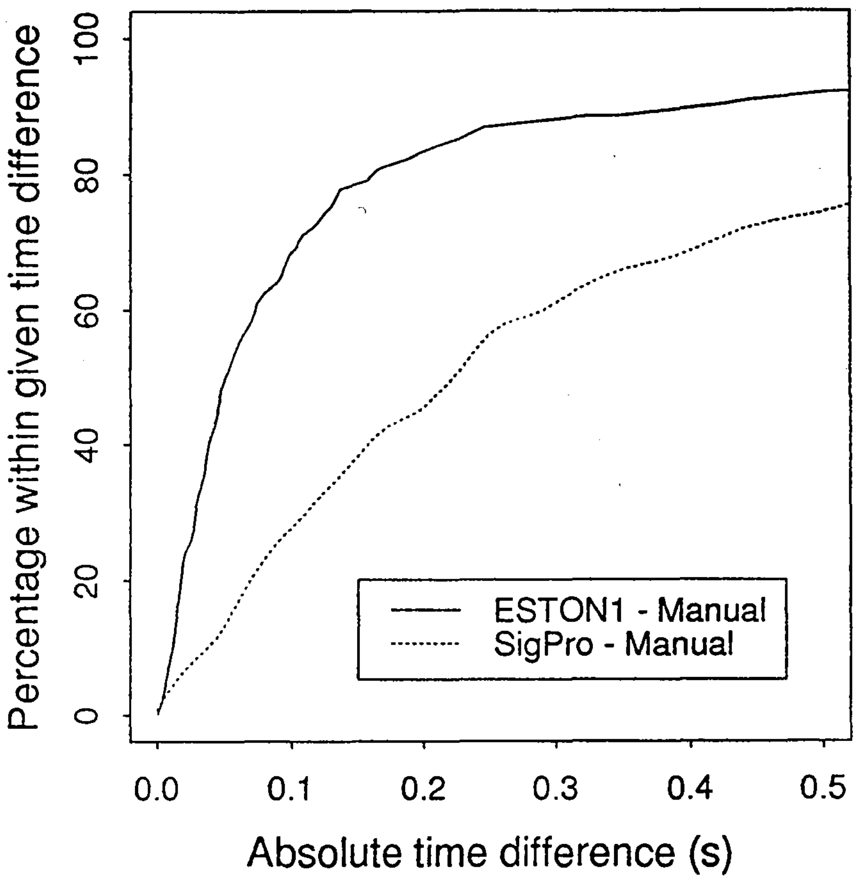


Fig. 7.4.5. These two curves show the percentage of the automatic onsets within a range of absolute time differences from the manual picks. For SigPro (dashed line), 50 percent of the onsets are within 0.23 s of the manual pick, whereas for ESTON1 (solid line) the 50 percent level (median) is as low as 0.05 s.