*Royal Norwegian Council
for Scientific and Industrial Research
(NTNF)*

NORSAR

NORSAR Scientific Report No. 2-92/93

Semiannual Technical Summary

1 October 1992 — 31 March 1993

Kjeller, July 1993

APPROVED FOR PUBLIC RELEASE, DISTRIBUTION UNLIMITED

7.6 An evaluation of the performance of the Intelligent Monitoring System

Introduction

The Intelligent Monitoring System (IMS) is a computer hardware and software system which analyzes data from a network of seismic stations (arrays and three-component stations) to automatically detect and locate seismic events. The events automatically declared by IMS are reviewed by an analyst and modified as appropriate.

The version in current operation at NORSAR is described in Bache et al (1993). This version of IMS provides for joint processing of data from the NORESS and ARCESS arrays in Norway, the FINESA array in Finland, the GERESS array in Germany, and the new (fall of 1992) array near Apatity on the Kola peninsula of Russia (see Fig. 7.6.1). In addition, data from the array installed at Spitsbergen in November 1992 (Mykkeltveit et al, 1992) are made available to IMS for interactive analysis; i.e., detections from this array are not yet automatically associated by IMS. Based on these data sources, IMS automatically produces a bulletin of local, regional and teleseismic events. The key module used by IMS in doing this is ESAL (Expert System for Association and Location). ESAL uses the detection information resulting from the signal processing (the SigPro module, containing automatic signal detection and characterization) performed separately for each array, and forms and locates events using artificial intelligence technologies, notably in the form of rule-based reasoning.

One of the basic objectives of IMS is to provide automatic event definitions of a quality that significantly reduces the burden on the seismic analyst. Operational experience with IMS is thus taken into account to produce enhancements to the system that result in performance improvements. NORSAR has tried to assist in this process by undertaking evaluations of IMS performance following the release of new versions by SAIC, the system developer. The results of such studies are discussed with SAIC, and taken into account in the next set of enhancements to the IMS.

The subject of this study is the outcome of another such evaluation of the IMS. The performance of the system was checked carefully during a recent one-week test period, and the focus was on the performance of ESAL. The performance statistics presented in the following thus basically reflect the quality of the automatic results produced by ESAL, and not the quality of the final event definitions after analyst intervention. In addition to this, we also point to some potential for improvements in SigPro that would enhance the overall performance of IMS.

Evlauation procedure

The evaluation was conducted by NORSAR analyst and seismologist staffs, who analyzed carefully and thoroughly complete IMS data for the 7-day period 26 April - 2 May 1993. The task was threefold, namely, (i) to characterize the automatic IMS event definitions, (ii) to modify these as deemed appropriate, and (iii) to check for missed events, i.e., events that were *not* defined by IMS, but where detections were available from SigPro that should allow ESAL to associate phases and form events. Task (ii) is important in providing information on the performance of various IMS algorithms. Examples here are statistics on retiming of phase onsets and renaming of regional phases. Task (iii) above was performed through various means: The bulletin of the GBF (Generalized Beamforming) processing, which uses the detection information produced by SigPro to locate regional events, was checked to see whether it contained events not declared by IMS. Likewise, the results from the single-array "ep"-processing performed at NORSAR based on the SigPro output was checked. In addition, completely independent bulletins like the NORSAR array bulletin and the PDE bulletin of the USGS were checked, basically to identify teleseismic events that IMS might have failed to catch, even if appropriate detections were available from SigPro.

IMS automatically produces "event plots" like the one shown in Fig. 7.6.2. These plots give a good starting point for the review process, as the inferences made by ESAL in forming and locating the events can be judged from these plots. The actual assessment of all events reviewed for this one-week evaluation period was made on the basis of using the interactive analysis tools offered by the Analyst Review Station.

Each event automatically declared by IMS was assigned to one of the folllowing five categories:

Acceptable events: In addition to events accepted without any modifications, this category includes events where the anlayst made relatively minor changes. The character of these changes was such that the original IMS location was not strongly affected, i.e., the resulting change in location should be less than 50-100 km for regional events. For teleseismic events the requirements on "acceptable" events were more relaxed. The modifications in this category usually amounted to retiming of phases, association and disassociation of phases, as well as renaming of phases, especially for single-array events (e.g., from Sn to Lg or vice versa, from Pg to Px, from Rg to Lg, etc.).

Seriously mislocated events: This category includes events that are real events, but where the event location is too far away from the true location to qualify for the "Acceptable events" category. For these cases, either the phase assignments were wrong, or phases not belonging to the same event were associated.

False events: This category consists of those events declared by the IMS that the analyst rejected, believing they were not real events.

Inconclusive events: For this category, the analyst was not able to reach a definite conclusion whether the events were real or not.

Missed events: This category includes events that were *not* declared by IMS, but where detections were available from SigPro, that should permit ESAL to associate phases and form events. In addition to such events, the analyst occasionally produces events by manually adding signal arrivals that were not detected by SigPro. An example here would be a regional event for which SigPro has detected a P phase but where the S phase, though visible to the analyst during interactive waveform analysis, has gone undetected. Such events are *not* counted as missed in the statistics presented in this report.

All events in these five categories are divided into regional and teleseismic events, based on their epicentral distance from the network:

Regional events: Events where the closest station is within 20 degrees of the epicenter.

Teleseismic events: Events where the distance to the closest detecting station exceeds 20 degrees.

Results and discussion

Table 7.6.1 summarizes the results of the characterization of the events automatically declared by IMS during the one-week test period, and in addition includes statistics on events missed by IMS. As seen from this table, nearly 80% of the events declared are considered to be acceptable, whereas the majority of the remaining ones are considered to be false.

All events in the category "acceptable" were considered by the analyst to be real seismic events with automatic location estimates that were either not changed during the subsequent interactive analysis, or that were slightly modified during this process through minor changes as described in the previous paragraph. Renaming of regional phases is one example of such modifications, and Table 7.6.2 offers statistics in this regard. Only phases for which the original arrival time was changed by less than 2.0 seconds are included in this table. This is done to exclude cases where a change in phase name was accompanied by a substantial change in the phase arrival time. It is noteworthy that only for one single case was a phase changed from P- to S-type by the analyst, and there were no cases where an S-type phase was changed to P. The extent of renaming can thus be characterized as being relatively modest, meaning that the automatic phase identification in ESAL now works very well.

As seen in Table 7.6.1, altogether 105 events automatically declared by IMS were rejected by the analyst as false, based on various kinds of evidence. We have taken a closer look at these events to see if there is parametric or other kind of information available that might permit ESAL to automatically reject these events. The following observations are made:

- For 42 (all regional) of these 105 events, there is, in the judgement of the analyst, parametric information available that might be used by ESAL to preclude the formation of an event. Examples of such parametric evidence are high or low Pn velocities, and frequency content of Pn and Lg phases well outside the expected range for these phases. The formation of these events might be precluded through the addition of new rules in ESAL in the form of consistency checks on the parameters pertaining to phases used in forming these events.
- 15 (also all regional) of the false events were rejected by the analyst because they were located close to an array in the network which showed no sign of any signal arrivals from this event. (It was checked that the closest array was operating nor-

mally in these cases.) This is an expample where contextual information could be used to automatically reject an event hypothesis, and an appropriate consistency check in ESAL might rectify the situation. For several of the events in this category, also parametric information indicated that the events were false.

- Altogether 18 events (both regional and teleseismic in this category) were judged by the analyst to be so-called "split" events, i.e., phase arrivals (often coda detections) belonging to a real event were used to define an additional, false event. Sometimes the arrival azimuth estimates for the phases used to define the split event deviated by 20^{o} or so from those of the phases used to define the real event, and it would be difficult or maybe even inadvisable to preclude formation of the second event.

We find that 27 of the false events originate from detections resulting from bad data (spikes and gaps in the data). For 5 of the events, it is not possible for the analyst to see any signal at all (not even after beamforming) in the traces, and there may be some malfunction of the detector in these cases. Possible remedies for these 32 events would amount to changes in SigPro, but it should be noted that considerable work has already been invested in preventing SigPro from declaring detections when bad data are recorded.

There are a few false regional events at distances around 10^{o} that fall into none of the categories dealt with above. For these events, the only reason for rejecting them is the impression left after close inspection of the waveforms. The S wavetrain is impulsive and of very short duration, and thus does not match the expected shape (emergent onset and a coda of some length). It is of course very difficult to reject such events automatically, at least until the AI technology is able to match the trained eye of a skillful analyst.

As seen in Table 7.6.1, there are 15 regional events that were missed by IMS in the sense that IMS had available detection information that should allow ESAL to associate phases and form and locate events. Only one of these events had detections on more than one array, and this is a small (local magnitude 1.2) Khibiny Massif event recorded at ARCESS and the Apatity array. Three of the missed one-array events were associated with double events (two mine blasts at the same site, 10 seconds or so apart), where IMS only defined one event. For 4 of the remaining 11 missed one-array events, the arrival azimuth estimates for P and S phases differed by more than 20^{o} (they were in the range $22.8\text{-}25.9^{o}$). This may be the reason why ESAL did not form these 4 events, but it appears that the remaining 7 events (with azimuth differences between P and S phases of less than 16.4^{o}) should all have been formed by ESAL.

Table 7.6.1 shows that 14 teleseismic events were missed by IMS. These were events defined in the reference bulletins, and for which ESAL had detections available (from 2 or more arrays) that apparently should have been associated. It will be necessary to have a closer look at all of these to determine why they were not formed by ESAL.

Conclusions and recommendations

Our main impression after having carefully analyzed one week of data is that the overall performance of IMS is now very satisfactory. For example, the rules used for automatic phase identification in ESAL appear to work very well. It is also observed that problems associated with earlier versions of IMS have now to a large extent been solved. There is, however, still room for some improvement, as discussed above and summarized in the following.

The number of false events may appear a bit high, and we have suggested some possible remedies that might help the IMS to automatically reject some of these. Such changes must, however, be tested very carefully to make sure they do not have unintended effects, like throwing out real events. In fact, in order to make sure that the system does not miss real events, we will just have to cope with a certain number of false events. This number can probably be reduced quite a bit from today's about 20% of the total number of events automatically declared by IMS, and it must remain a goal for IMS to minimize the burden on the analyst by defining as few false events as possible.

Events missed by IMS represent a more serious problem than that of the false events. Due to the large amounts of data processed by the IMS and the limited manpower resources available for interactive analysis of the automatic IMS results, it is unlikely that the analyst review process will pick up the events missed by ESAL. Keeping in mind the basic purpose of IMS, it is therefore of utmost importance that ESAL captures all real events, for which there is a solid basis for phase association and event formation. We have seen in the aforegoing that some of the missed regional events were associated with double mining blasts. Although this is a situation where a trained analyst could pick up the missed event when inspecting the waveform traces, it will certainly present a challenge to capture all such events and at the same time avoid formation of split events. All except one of the other regional events missed were very small one-array events. Still, it is necessary to have a close look at ESAL to rectify this problem, as well as the problem of the missed teleseismic events.

As we have already seen, IMS performance could also be enhanced through certain modifications to SigPro. We will here touch upon another aspect where changes to SigPro might be beneficial: Figs. 7.6.3 and 7.6.4 provide statistics on retiming of the phases Pn and Pg, respectively, during the course of analyst review of the data for the one-week evaluation period. The figures show the differences between the arrival time as automatically determined by SigPro and the arrival time as determined by the analyst during the review process, plotted versus the SNR of the Pn or Pg phase, calculated from the detecting beam. Only phases that after analyst review retained their original, automatic phase assignment (Pn or Pg) and in addition correspond to real seismic events, are included in Figs. 7.6.3 and 7.6.4. The figures show standard deviations of the order of half a second for the differences in the arrival time estimates, and there are appreciable differences even for high SNR phases. This indicates that there should be quite some potential for improvement in the automatic estimation of phase arrival times. Section 7.2 of this Semiannual Technical Summary presents an approach that might be implemented in SigPro and that holds considerable promise to improve the automatic onset times.

The current version of IMS makes use of some region-specific knowledge. Further enhancements to IMS performance are likely to be obtained through introduction of additional such knowledge, and section 7.3 of this Semiannual Technical Summary demonstrates how event locations may be significantly improved using region-specific knowledge.

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References

Bache, T., 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.*, in press.

Mykkeltveit, S., A. Dahle, J. Fyen, T. Kværna, P.W. Larsen, R. Paulsen, F. Ringdal and I. Kuzmin (1992): Extensions of the Northern Europe Regional Array Network -- New small-aperture arrays at Apatity, Russia, and on the Arctic island of Spitsbergen, in *Semiannual Technical Summary 1 April - 30 September 1992*, NORSAR Scientific Report No. 1-92/93, Kjeller, Norway.

	Regional	Tele-seismic	Total
Acceptable events	384	67	451
Seriously mislocated events	5	4	9
False events	97	8	105
Inconclusive	0	4	4
Total number of events declared			569
Missed events	15	14	29

Table 7.6.1 Characterization of all events automatically declared by IMS during the seven-day period 26 April - 2 May 1993 (see text for explanation of the various categories). The table also includes statistics on events missed by the IMS.

Analyst

ESAL	Pn	Pg	Px	Sn	Lg	Rg	Sx
Pn	213	19	2				
Pg	11	203	24	1			
Px	2	2	60				
Sn				34	5		9
Lg				7	325	7	24
Rg					6	30	7
Sx				1	20		75

Table 7.6.2 The table shows the ESAL automatic phase assignments versus analyst assignments made during interactive analysis, for all regional phases that were used by IMS to define regional events during the time period 26 April - 2 May 1993.

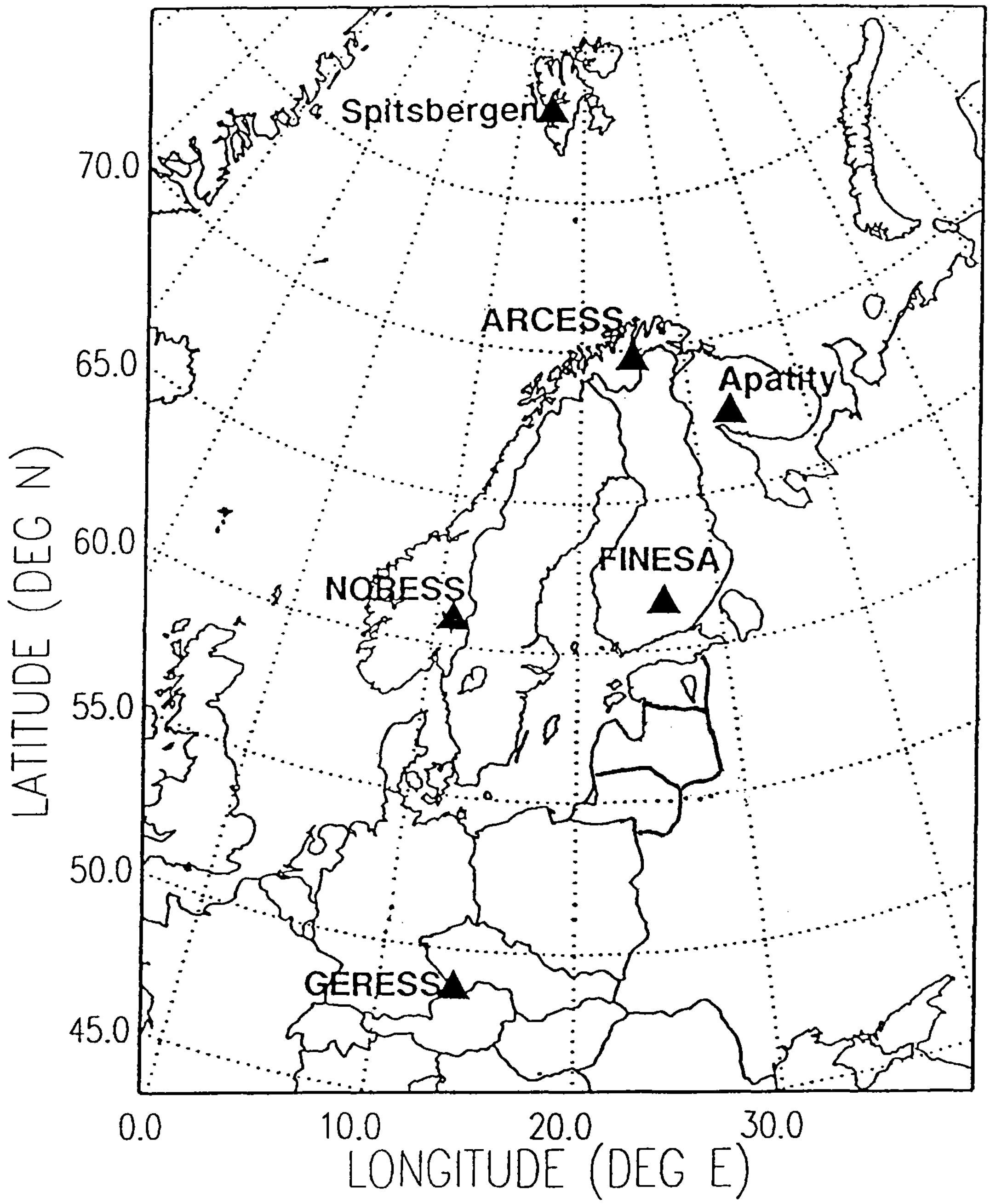


Fig. 7.6.1 The network of six regional arrays in northern Europe.

Date	Time	Lat	Lon	Smajor	Sminor	Strike	Depth	Mb	Ms	Ml	Orid
4/26/93	10:46:10.5	59.2388	27.9150	19.7685	14.9955	105.29	0.0000	-	-	2.26	64863

EUROPEAN USSR

FIAO 2.385 338.38 156.78

IPhase	Phase	Time	Timeres	Azimuth	Azres	Vel	Snr	Amp	Freq	Arid	Orid	Qual
Lg	-	10:46:23.8	-	22	-	2.9	15.6	38	1.0	769524	0	-
Pn	-	10:46:35.1	-	353	-	5.9	78.6	165	1.2	769526	0	-
Pg	Pg	*10:46:51.9	-1.4	158	1	7.0	117.6	9	10.0	769527	64863	-
Lg	Sx	*10:47:10.3	-	149	-8	4.3	7.7	50	1.9	769528	64863	-
Sx	Lg	*10:47:25.5	0.3	162	6	4.0	11.5	50	3.3	769529	64863	-
Sx	Rg	*10:47:39.6	0.7	164	8	3.5	8.4	176	1.0	769530	64863	-
N	-	10:47:48.0	-	175	-	2.5	7.2	205	1.2	769531	0	-
Pn	-	10:50:17.9	-	207	-	8.3	3.0	7	1.0	769540	0	-
N	-	10:50:22.9	-	2	-	2.5	3.0	1	1.4	769541	0	-

NRAO 8.303 287.39 93.18

IPhase	Phase	Time	Timeres	Azimuth	Azres	Vel	Snr	Amp	Freq	Arid	Orid	Qual
Pn	Pn	*10:48:12.2	1.3	93	0	8.5	11.7	1	5.3	769533	64863	-
Sn	Sn	*10:49:46.1	4.4	77	-16	4.7	2.7	2	3.8	769538	64863	-
Sx	Sx	*10:50:01.9	-	86	-7	4.6	2.5	4	2.9	769539	64863	-
Sx	Lg	*10:50:30.3	-0.3	96	3	3.8	5.4	8	2.6	769542	64863	-
Lg	Sx	*10:50:37.3	-	91	-2	4.2	4.3	2	3.1	769544	64863	-

APAO 8.663 12.94 197.49

IPhase	Phase	Time	Timeres	Azimuth	Azres	Vel	Snr	Amp	Freq	Arid	Orid	Qual
Sx	-	10:48:55.1	-	93	-	3.0	7.1	2	5.9	769535	0	-
Sx	-	10:48:56.8	-	94	-	2.9	6.1	2	6.2	769536	0	-
Sx	-	10:49:02.5	-	85	-	3.7	4.1	7	3.1	769537	0	-
N	-	10:51:19.9	-	95	-	2.8	3.2	2	6.7	769545	0	-
N	-	10:51:24.0	-	95	-	2.9	3.3	2	6.2	769547	0	-

ARAO 10.347 355.31 173.12

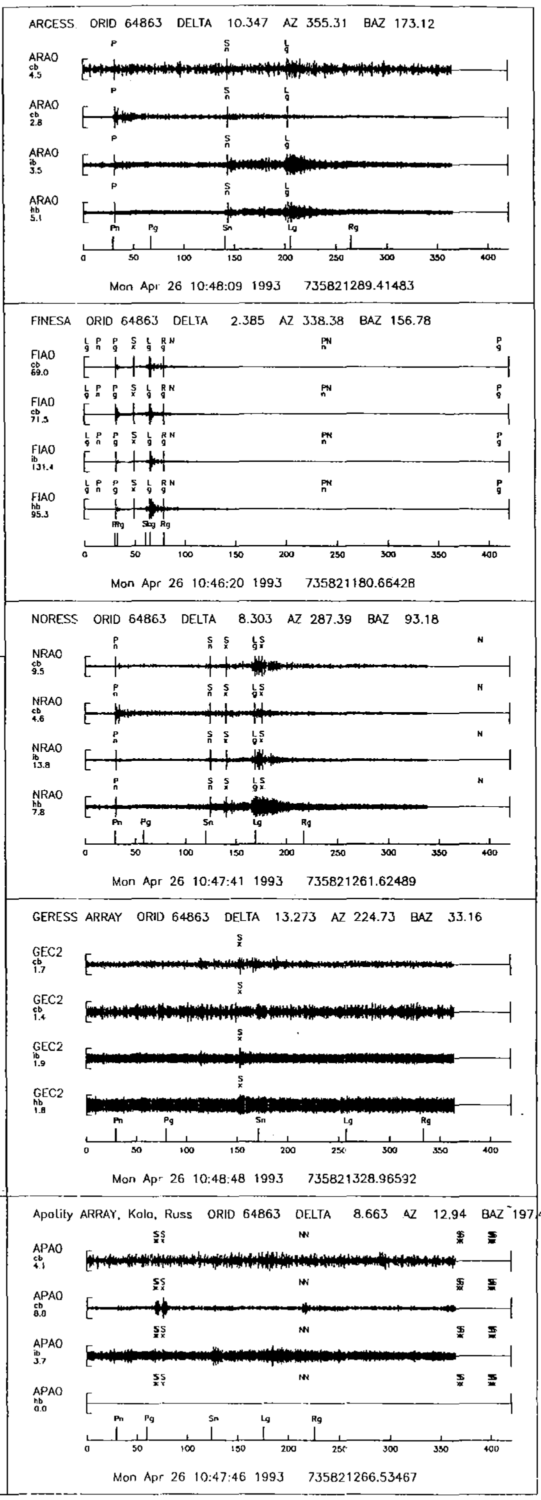
IPhase	Phase	Time	Timeres	Azimuth	Azres	Vel	Snr	Amp	Freq	Arid	Orid	Qual
Pn	P	*10:48:40.7	1.3	173	-0	8.6	12.0	0	4.8	769534	64863	-
Sn	Sn	*10:50:33.1	2.8	188	15	4.6	3.3	1	4.0	769543	64863	-
Sx	Lg	*10:51:32.1	-2.5	167	-6	3.4	2.9	5	1.8	769548	64863	-

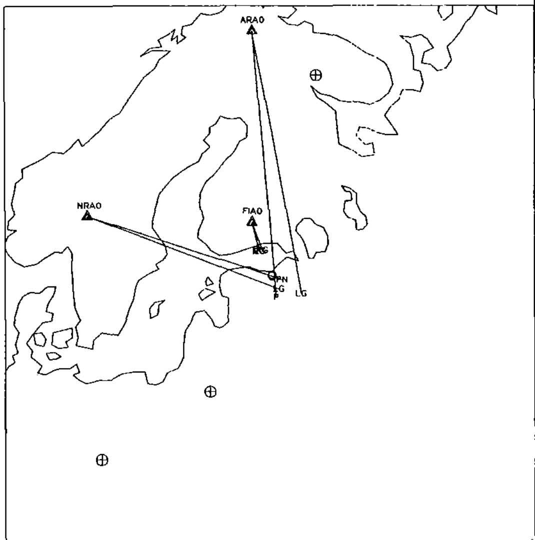
GEC2 13.273 224.73 33.16

IPhase	Phase	Time	Timeres	Azimuth	Azres	Vel	Snr	Amp	Freq	Arid	Orid	Qual
Sx	-	10:51:22.3	-	9	-	4.0	4.1	1	2.3	769546	0	-

SPAO 19.310 352.88 161.97

IPhase	Phase	Time	Timeres	Azimuth	Azres	Vel	Snr	Amp	Freq	Arid	Orid	Qual
Pgn	-	10:50:52.3	-	257	-	9.1	3.1	1	2.4	769639	0	3
Pgn	-	10:50:58.2	-	200	-	7.2	2.7	1	2.4	769640	0	3
Pgn	-	10:50:59.7	-	283	-	4.4	3.1	0	4.1	769641	0	4
Pgn	-	10:53:12.2	-	77	-	4.1	4.0	2	1.8	769642	0	1





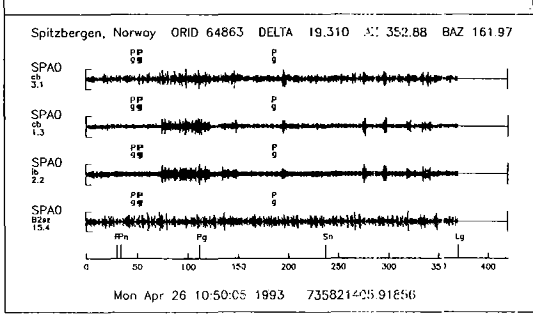


Fig. 7.6.2. A typical example of a plot automatically produced by IMS, basically showing the judgements and inferences made by ESAL in associating phases at the various arrays and forming this event in Estonia.

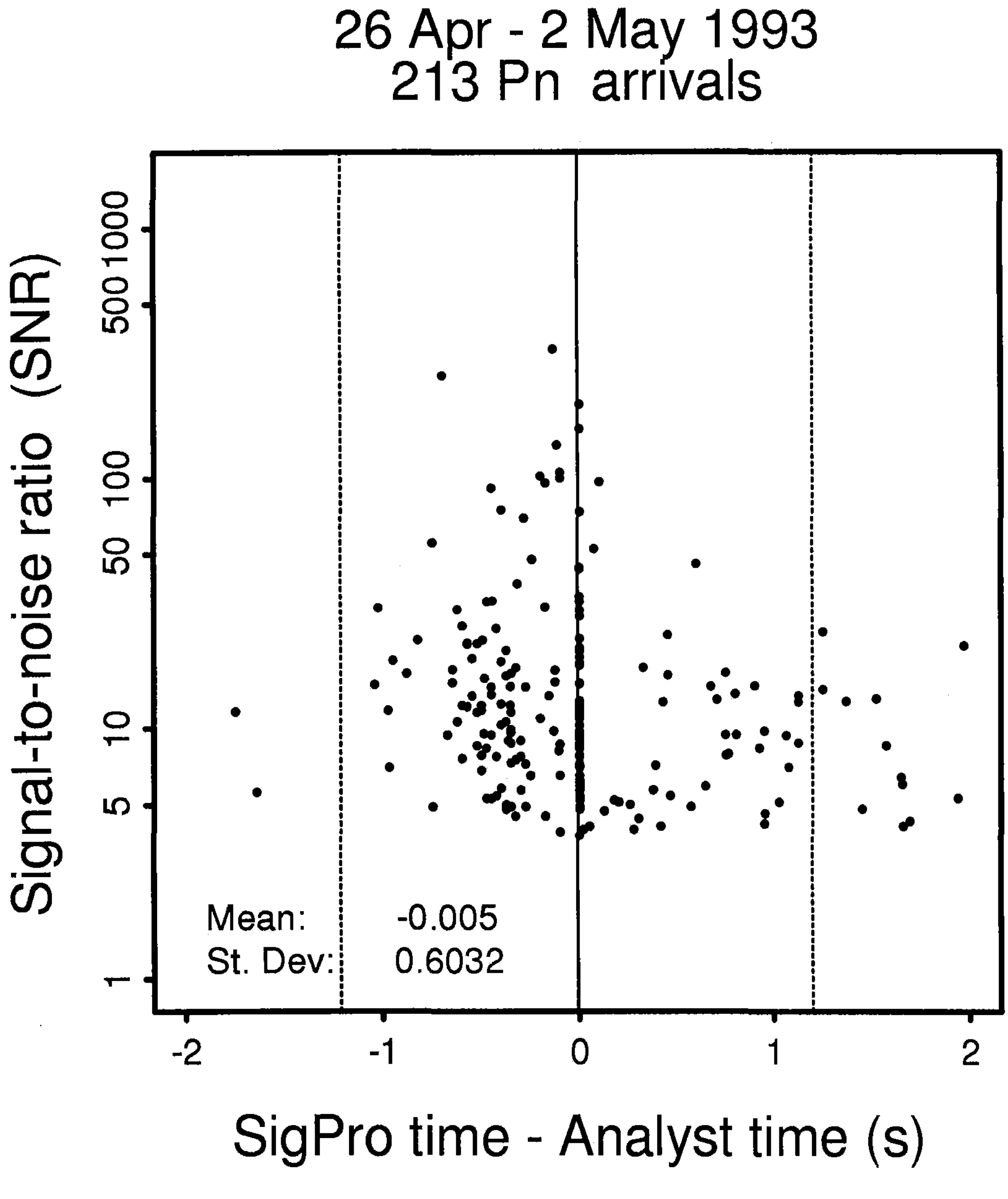


Fig. 7.6.3. The figure shows differences between arrival times as determined by SigPro and arrival times determined by the analyst during review, plotted versus SNR, for Pn phases used by IMS to form events during the evaluation period 26 April - 2 May 1993. The mean value of the arrival time differences is marked by a solid vertical line, whereas the two strippled lines denote ± 2 standard deviations.

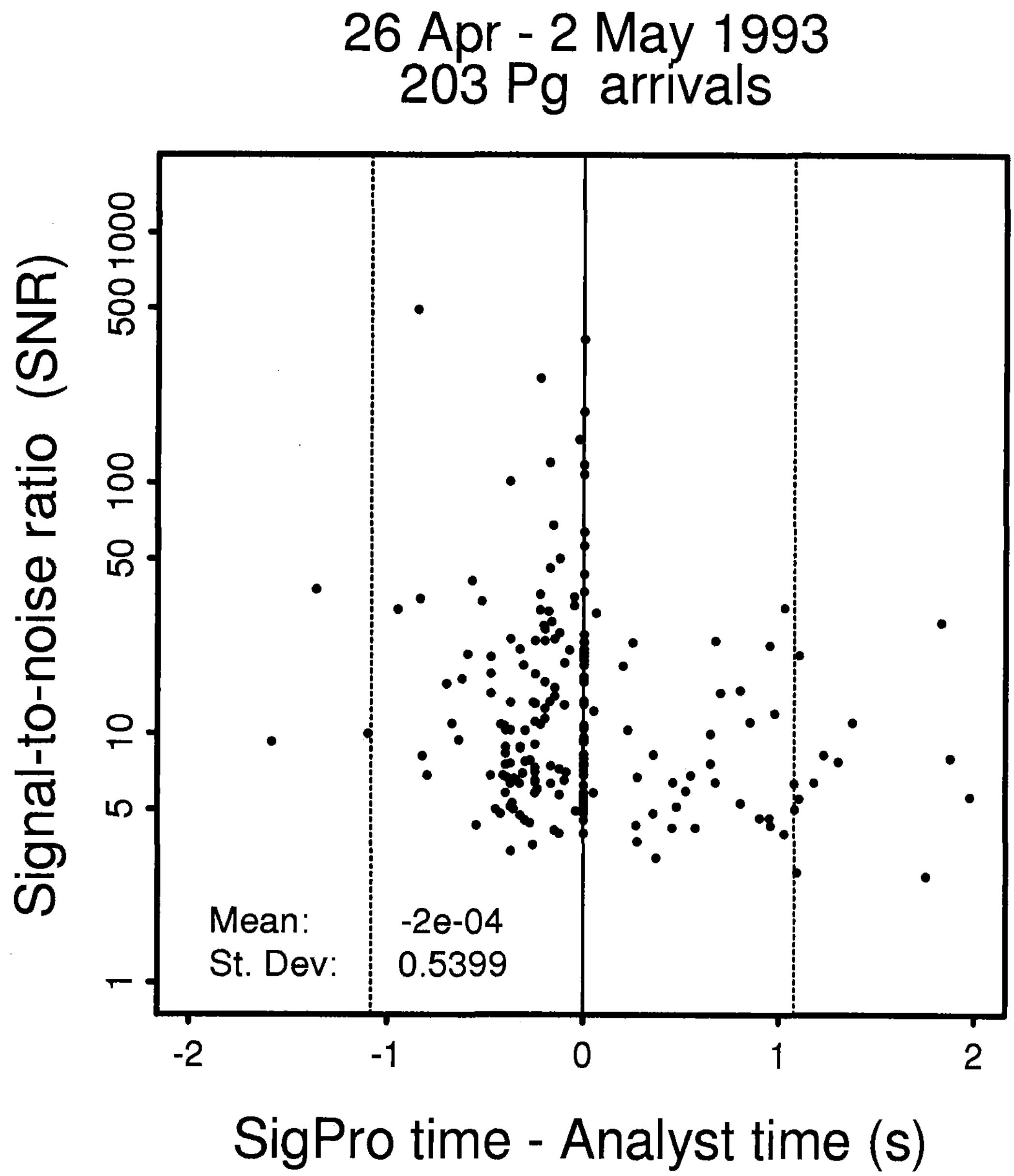


Fig. 7.6.4. Same as Fig. 7.6.3, but for the Pg phase.