7.3 Development of improved NORSAR time delay corrections

Introduction

The large aperture NORSAR array began operation in 1970, and comprised initially a configuration of 22 subarrays distributed over a diameter of 100 km. After six years of experimental operation, the array was modified on 1 October 1976 to a reduced configuration which was more suitable for an automated, operational system, and the 7 best subarrays (in the NE part of the original array) were selected for this purpose. This configuration is still in operation today, with each subarray comprising 6 SP and one 3-component BB seismometer over an area 8 km in diameter. The total aperture of NORSAR is now 60 km (Fig. 7.3.1).

A complete technical refurbishment of the NORSAR array was carried out during 1992-1995, and the array will in 1996 be ready for participation in the GSETT-3 experiment. However, in order to take full advantage of the NORSAR capabilities, it is desirable to update the beam deployment and revise the time delay anomalies taking into account the improved precision made possible from the increased sampling rate (40 Hz against previously 20 Hz) and the accumulated data base of reference events. This paper gives a progress report on the work carried out until now and should be seen in connection with previous reports on this subject (Fyen, 1995a, 1995b).

Procedure

The main points of revising the NORSAR beam deployment, as described in more detail in Fyen (1995a) are summarized as follows:

Data base development

We are compiling a data base of several hundred well-recorded and well-located events, dating back to the initial NORSAR establishment in 1970. Emphasis is on obtaining a good geographical distribution of epicenters. Among the events of special interest here will of course be the known nuclear explosions, especially the large number of PNEs in the former Soviet Union.

Reference locations

We have primarily made use of ISC or PDE location estimates for reference purposes. In cases where more accurate locations have been published (e.g., in recent literature or in local bulletins), these locations will be used. Additionally, location of recent events calculated by the GSETT-3 IDC is a helpful supplement.

Channel correlation

The reference events are systematically analyzed using a semi-automated channel correlation procedure, and verified by an experienced analyst. The correlation is based on the first cycle(s) of the P-signal, in an optimum filter band. A resampling procedure is applied before the correlation in order to improve the timing resolution.

Consistency checking of the delay anomalies

By using several reference events from nearby locations, it will be possible to make a systematic search for outliers. This procedure ensures that the data are consistent to the extent possible.

Interpolation in inverse velocity space

As originally done by IBM in the LASA/NORSAR development (Berteussen, 1974), the data base of time delay anomalies will, if necessary, be subjected to two-dimensional interpolation in inverse velocity space, to obtain anomaly estimates for regions in which no events have been recorded. For many regions, we expect the coverage to be dense enough so that interpolation is unnecessary.

Beam deployment

A revised beam deployment for NORSAR is being developed on the basis of the results of this study. The beamforming gain at various frequencies has been compared to the previous beams, so as to quantify the improvements achieved by this project.

Use of single-sensor anomalies

In contrast to the original time delay anomalies for NORSAR, which were developed only for subarray beams, the new set of delays are compiled as far as possible on an individual seismometer basis. This implies that even detection at the subarray level should be significantly improved, especially at high frequencies. However, in some regions the SNRs of the reference events are insufficient for single sensor analysis, and subarray beams are used in these cases.

For further details on NORSAR detection processing, slowness estimation and measurement of time delay anomalies, reference is made to Fyen (1995a).

Data analysis

Data base

The data base analyzed so far comprises 55 reference events, as listed in Table 7.3.1. The events are distributed globally, but for some areas several close events have been analyzed in order to compare the consistency of the results.

Correlation procedure

For each event, an interactive correlation procedure was carried out, as described by Fyen (1995a) and illustrated in Figs. 7.3.2 and 7.3.3. The first of these figures illustrates time picks within one subarray, whereas the second figure shows time-aligned traces from the entire array after automatic waveform correlation. It is seen that the correlation is excellent for the first two cycles, whereas scattering effects cause the remainder of the wavetrain to be far less coherent across the array.

Location anomalies

For each event, a plane wave was fitted by least squares, using the final time picks. This enabled us to calculate an "uncalibrated" location based on observed azimuth and velocity (using IASPEI tables to convert velocity to distance). Fig. 7.3.4 compares these uncalibrated locations with the "true" location of the reference events. Not unexpectedly, the azimuth is relatively more reliable than the distance, but even the azimuth needs correction in some cases. The location errors are generally quite consistent over limited areas, implying that consistent correction will be possible to apply.

SNR gains

We expect that the SNR gains achieved by the new time delay corrections will be significant for events of dominant high frequencies. The new time delays will make full array processing feasible in a filter band as high as 2-4 Hz, as compared to the current 1.2-3.2 Hz filter. Fig. 7.3.5 shows the relative SNR on the array beam for the 55 reference events using 2-4 Hz filter with the new corrections and 1.2-3.2 Hz for the old corrections. In some cases, a gain by a factor of 5 (0.7 m_b units) is observed. It is also seen that for some events (with low-frequency signal content) the 1.2-3.2 filter is still better than 2-4 Hz. This shows that it will be necessary to apply a set of narrow band filters for optimum detectability, similar to what is done for the NORESS-type arrays.

The new time delays are in general not expected to give large gains in the 1.2-3.2 Hz band for areas where the old calibration data base is well developed. For example, Fig. 7.3.6 shows array beam (new and old time delays) for a scaled-down signal (a factor of 200) from a Lop Nor explosion. The SNR for the new set is slightly better, but not by a large amount. Nevertheless, the new time delays should give significant gain in the 1.2-3.2 Hz band for areas where the old data base is less well established, and this will be investigated further.

Future plans

The data base will be extended to comprise several hundred well-recorded events, using the same analysis procedures as described above. This is expected to provide significantly more accurate azimuth/velocity estimates for detected events world wide, and would also contribute to improved detectability by enabling full NORSAR array processing in additional high-frequency filter bands.

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References

Berteussen, K.-A. (1974): NORSAR location calibrations and time delay corrections, NORSAR Sci. Rep. 2-73/74, Kjeller, Norway.

Fyen. J. (1995a): Time delay measurements and NORSAR large array processing, NORSAR Technical Report, June 1995, Kjeller, Norway.

Fyen, J. (1995b): NORSAR large array processing and time delay measurements. NORSAR Semiannual Tech. Summary 1 October 94 - 31 March 95, NORSAR Sci. Rep. 2-94/95, Kjeller, Norway.

Event	Year	Doy	hh	mm	sec	Lat	Lon	Vel	Azi
nao71157b	1971	157	04	02	57.3	49.98	77.74	13.14	76.11
nao71310	1971	310	22	00	00.1	51.47	179.11	17.53	8.17
nao72265	1972	265	15	30	00.2	37.08	-116.04	18.79	318.32
nao73137	1973	137	16	00	00.0	39.79	-108.37	17.69	313.80
nao73157	1973	157	13	00	00.1	37.25	-116.35	18.78	318.63
nao73172	1973	172	14	44	59.3	37.08	-115.99	18.79	318.29
nao74138	1974	138	02	34	55.4	26.99	71.80	14.99	102.01
nao75051	1975	051	05	32	57.6	49.76	78.09	13.16	76.00
nao75070	1975	070	05	42	57.6	49.76	78.23	13.17	75.92
nao75117	1975	117	05	36	57.3	49.94	79.02	13.19	75.15
nao75159	1975	159	03	26	57.6	49.75	78.08	13.17	76.06
nao75170	1975	170	13	00	00.1	37.35	-116.32	18.76	318.65
nao75181	1975	181	03	26	57.3	49.98	78.92	13.19	75.13
nao75224	1975	224	15	00	00.0	70.76	127.12	13.50	26.95
nao75302	1975	302	04	46	57.3	49.92	78.91	13.19	75.16
nao76015	1976	015	04	46	57.3	49.80	78.25	13.17	75.82
nao76080	1976	080	04	34	00.0	41.76	88.67	14.45	76.04
nao76211	1976	211	04	59	58.0	47.81	48.10	12.20	105.43
nao76310	1976	310	03	59	56.9	61.52	112.73	13.83	42.60
nao77132	1977	132	11	17	50.0	39.29	117.71	16.81	56.14
nao77161	1977	161	00	40	58.9	39.62	117.99	16.77	55.79
nao77170	1977	170	11	47	23.9	47.12	151.09	17.53	28.45
nao77222	1977	222	22	00	02.0	50.95	110.78	14.80	53.11
nao77330	1977	330	22	46	52.0	39.47	117.99	16.80	55.86
nao77347	1977	347	01	14	20.5	17.33	-54.91	16.76	257.46
nao78066a	1978	066	02	48	39.1	31.92	137.62	19.88	44.45
nao78066b	1978	066	02	48	47.6	31.99	137.61	19.88	44.45
nao78102	1978	102	03	42	03.7	56.52	-152.61	16.54	349.97
nao78143	1978	143	07	50	28.3	31.07	130.10	19.41	50.81

Event	Year	Doy	hh	mm	sec	Lat	Lon	Vel	Azi
nao78204	1978	204	14	42	39.5	22.19	121.42	20.58	61.88
nao78205	1978	205	08	06	17.0	26.61	-88.82	18.42	291.83
nao78221	1978	221	17	59	58.1	63.65	125.34	14.10	34.36
nao78264	1978	264	14	59	57.6	66.53	86.26	12.65	47.40
nao78290c	1978	290	13	59	58.0	63.21	63.26	12.16	62.06
nao78357	1978	357	11	23	13.7	23.17	122	20.40	60.96
nao79017	1979	017	07	59	55.8	47.87	48.06	12.20	105.25
nao79059	1979	059	21	27	06.6	60.74	-141.56	15.64	344.40
nao79082	1979	082	19	32	30.9	18.02	-69.04	18.01	270.53
nao79236	1979	236	16	59	28.9	41.16	108.13	15.84	62.01
nao79237	1979	237	08	44	04.5	10.72	-41.68	16.73	241.38
nao79277	1979	277	15	59	58.0	60.66	71.44	12.47	63.78
nao79297	1979	297	05	59	56.7	47.79	48.11	12.20	105.34
nao79327	1979	327	23	40	29.7	4.81	-76.20	22.03	270.09
nao80084	1980	084	03	59	50.3	52.94	-167.70	17.32	359.28
nao80124	1980	124	03	30	54.5	9.95	43.16	15.52	141.15
nao81306	1981	306	21	10	25.5	12.18	92.87	19.32	91.30
nao82001	1982	001	18	51	02.6	26.84	142.74	21.83	42.41
nao82098	1982	098	02	41	16.9	18.51	86.31	17.40	93.75
nao82100	1982	100	16	25	34.5	17.45	-83.47	19.79	282.62
nao82172	1982	171	23	52	30.2	-20.40	40.57	24.40	145.75
nao82182	1982	182	07	41	53.7	51.39	-179.94	17.56	7.57
nao83093	1983	093	02	50	02.8	8.80	-83.11	22.01	278.00
nao83094	1983	094	02	51	34.5	5.71	94.72	21.13	92.90
nao83102	1983	102	12	07	54.4	-4.84	-78.09	24.27	267.06
nao83274	1983	274	12	57	59.5	45.50	150.78	17.80	29.27
nao84004	1984	004	22	40	41.8	45.40	151.31	17.87	28.84

Table 7.3.1. List of events used in this study.

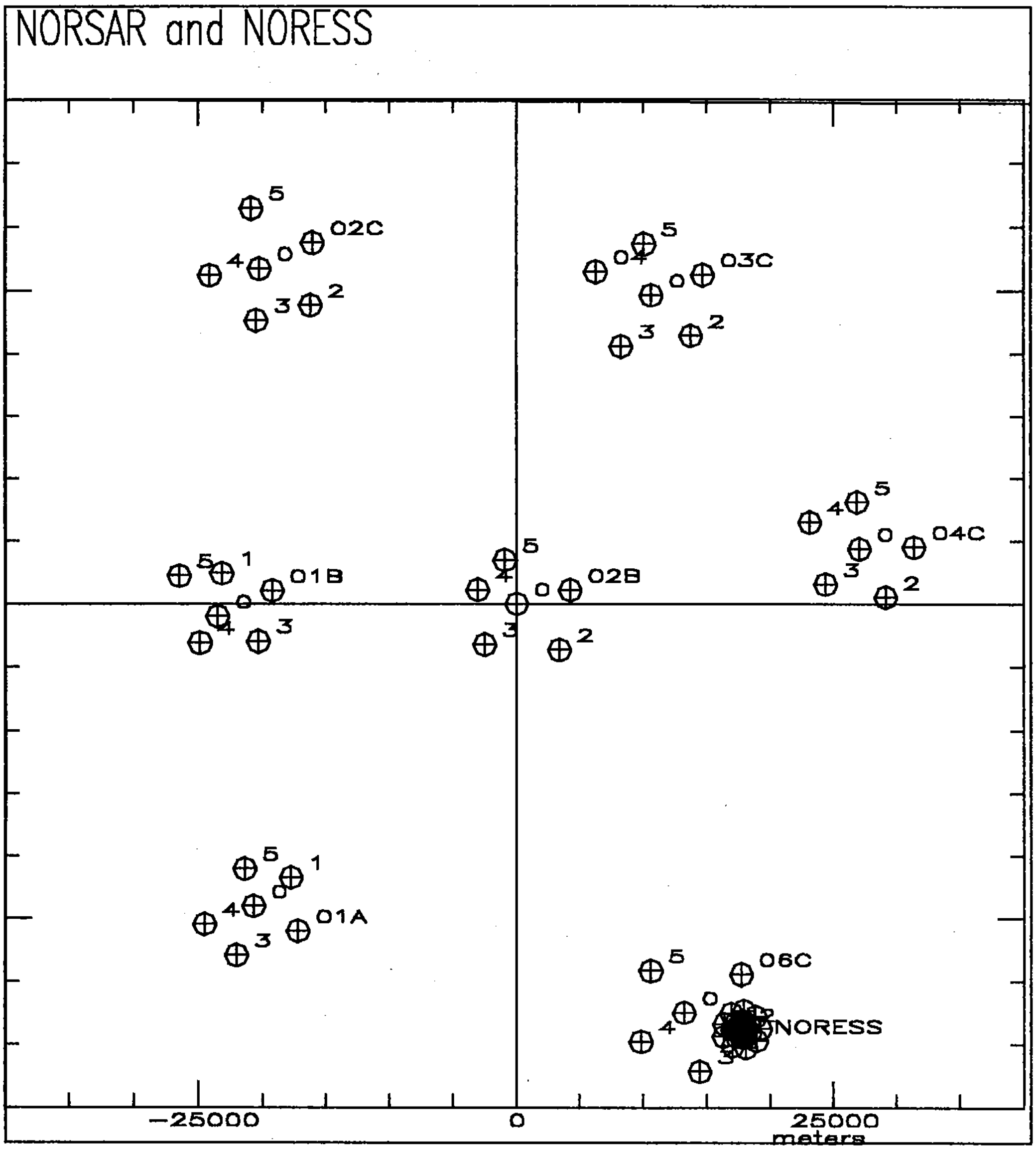

Fig. 7.3.1. Configuration of the large aperture array NORSAR and small aperture array NORESS. The NORESS array is co-located with the NORSAR subarray 06C. The diameter of NORSAR is about 60 km and the diameter of NORESS is about 3 km. Each instrument site is marked with a circle and a cross.

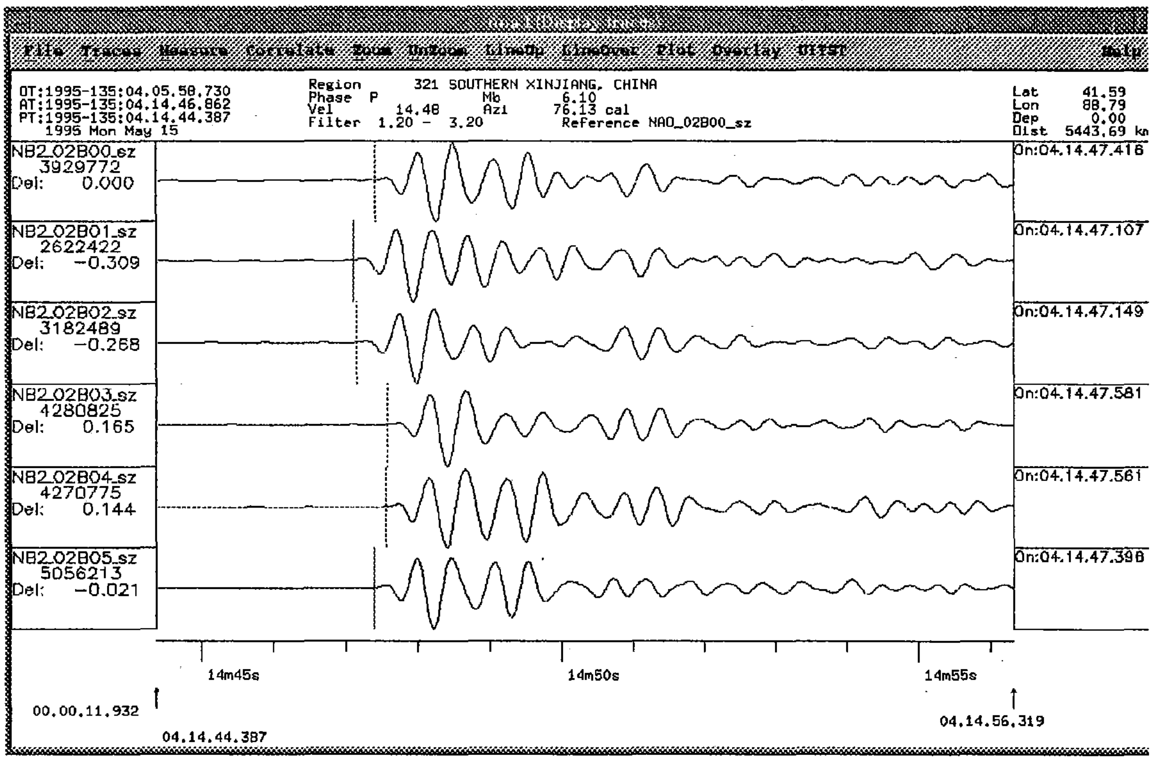

Fig. 7.3.2. NORSAR interactive tool for time picks. A trace-cursor containing the reference trace with reference arrivaltime mark is available to the user, but not visible on this figure. Using this cursor, the analyst can easily correlate the signals to find best arrival time pick.

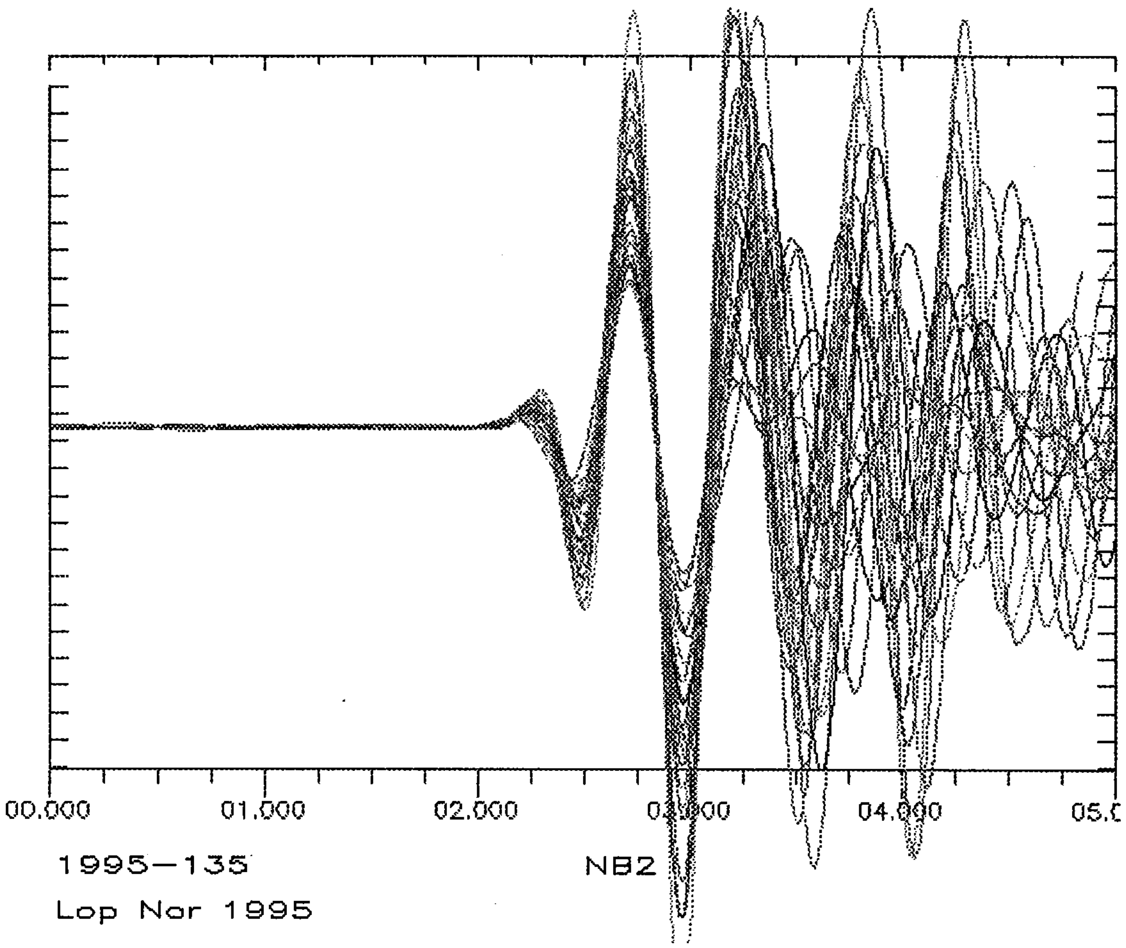

Fig. 7.3.3. NORSAR single sensors filtered 1.2-3.2 Hz and shifted with time delays picked by automatic correlation. Traces are plotted on top of each other in the same amplitude scale. The resulting least squares plane-wave fit gives: Observed velocity 16.44, azimuth 79.73; Calibrated velocity 17.37, azimuth 77.80; IASPEI velocity 14.48, azimuth 76.13.

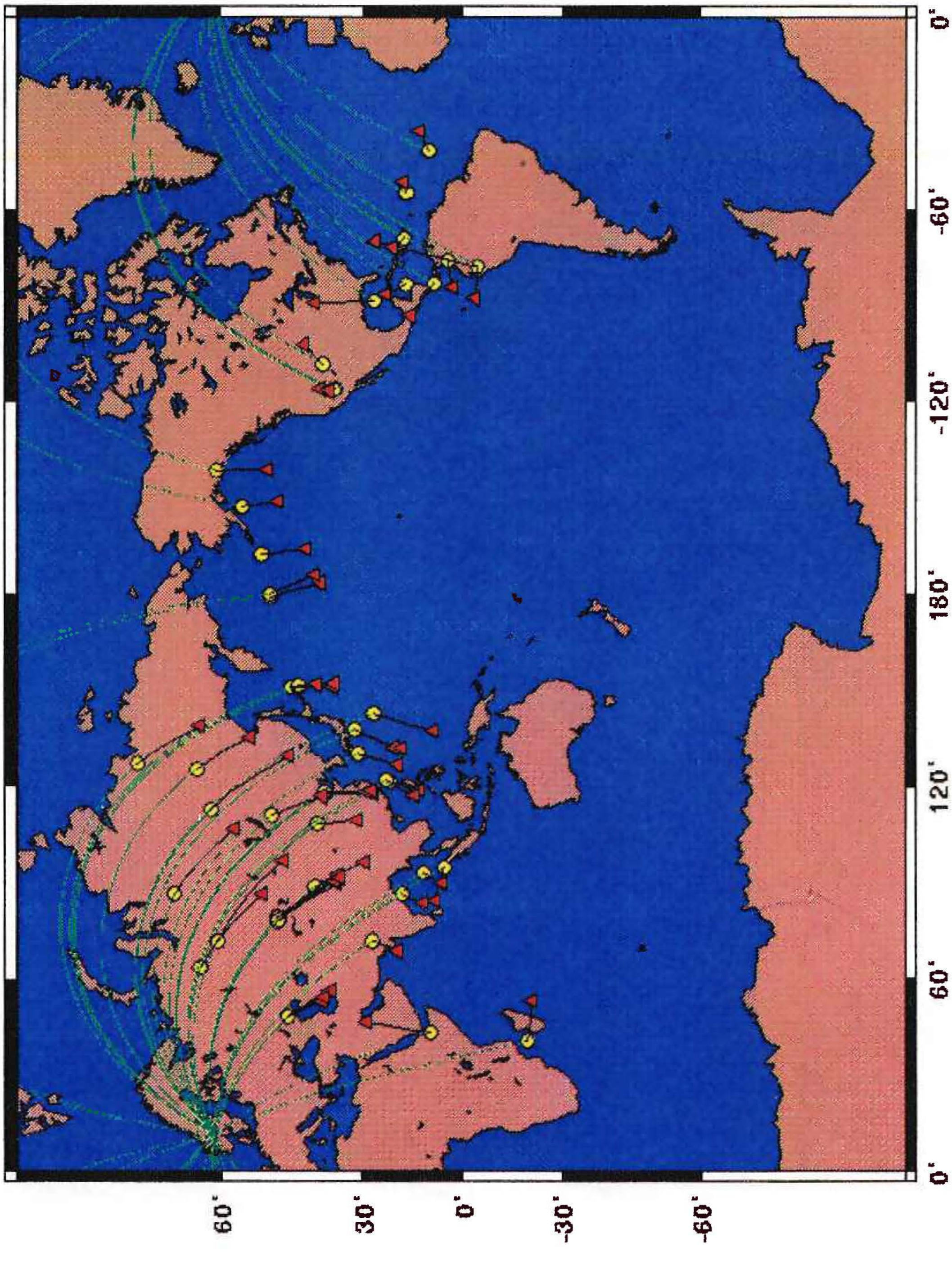

Fig. 7.3.4. Map of reference events used in analysis. The circles correspond to ISC/PDE locations. The triangles show locations corresponding to slownesses estimated by least squares fit to observed time delays.

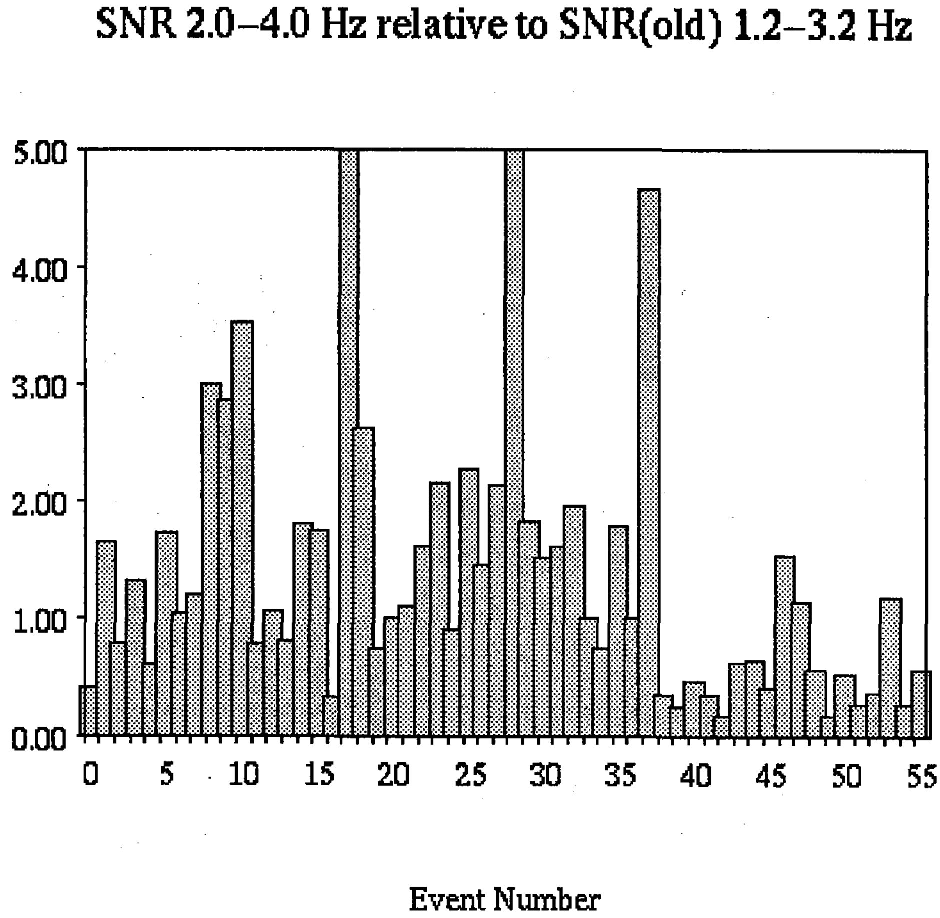

Fig. 7.3.5. Relative SNR between best beam using filter 2.0 - 4.0 Hz and new time delays and best beam using filter 1.2 - 3.2 Hz and old time delays.

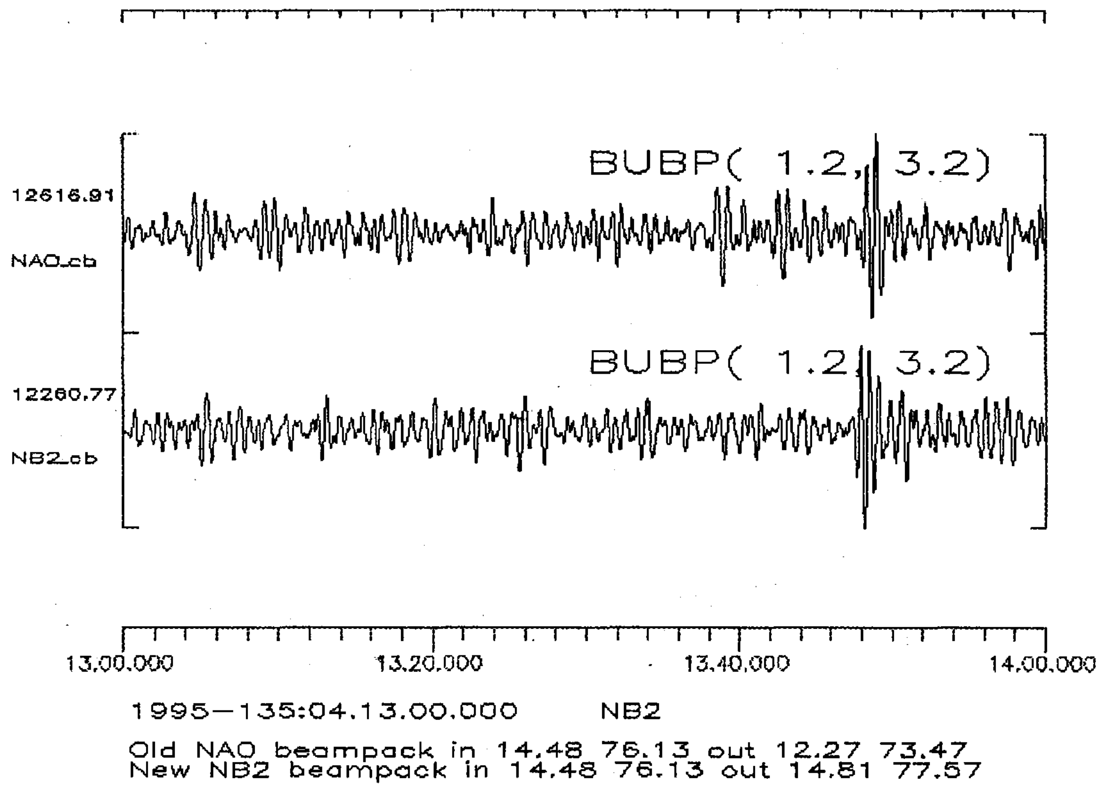

Fig. 7.3.6. NORSAR signal from the 15 May 1995 Lop Nor explosion scaled down by factor of 200 and added to noise preceding main onset. The upper trace shows resulting beam after beampacking using filter 1.2 - 3.2 and old time delay corrections. The observed velocity and azimuth is 12.27, 73.47. The lower trace is resulting beam from beampacking using new time delay corrections. Resulting observed velocity and azimuth is 14.84, 77.57. IASPEI theoretical values are 14.48, 76.13.