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7.3 NORSAR large array processing and time delay measurements

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). This array configuration enables excellent teleseismic detectability and location capability as illustrated in Fig. 7.3.2.

A complete technical refurbishment of the NORSAR array was carried out during 1992-94, and the array will this year 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.

Procedure

The main points of revising the NORSAR beam deployment are summarized as follows:

Data base development

We will compile a data base of several hundred well-recorded and well-located events, dating back to the initial NORSAR establishment in 1970. Emphasis will be 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 will primarily make 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 will be 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, and otherwise ensure that the data are consistent to the extent possible.

Interpolation in inverse velocity space

As originally done by IBM in the LASA/NORSAR development, 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 will be developed on the basis of the results of this study. The beamforming gain at various frequencies will be 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 will be compiled on an individual seismometer basis. This implies that even detection at the subarray level should be significantly improved, especially at high frequencies.

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

Interactive tool for picking arrival times

To create a data base with time delays, it is necessary to measure arrival times at every single site of the current NORSAR array for each reference event.

Knowing hypocenter parameters for the event, we can predict arrival times and slowness for the actual phase, using the IASPEI91 travel time tables.

In practice, the analyst should carefully define and pick the arrival time at a reference site, e.g. NB2_sz. Let this time be A_{ref}. Then arrival times A_i of all other sites will be measured using an interactive program developed for this purpose. This interactive tool is illustrated in Figs. 7.3.3 and 7.3.4.

Initial analysis

We describe in the following results from analyzing six events from the Philippine islands, using the interactive analysis tool. Table 7.3.1 shows a list of the events with parameters from different agencies.

In order to explain Table 7.3.1, let us recall that the NORSAR DP/EP automatic processing consist of three steps. First, Detection Processing - DP, which normally gives one or more detections for the same phase. The next step is beampacking for each detection to refine the slowness estimate and give location for each detection. The third step is grouping of the detections to declare one event and report an automatic event bulletin. Thereafter the analyst can interactively refine the solution, by adjusting onset time, slowness estimate, amplitude or period. Alternatively, the analyst can accept the automatic solution. Table 7.3.1 lists solutions for one or more of the processing steps with a comment field describing the associated processing steps. Here, the comment "C057" refers to the automatic first trigger solution for coherent beam C057, meaning that this beam is the first detection if there are more than one detection for that event. The comment "analyst" means that this is the analyst-reviewed solution.

After having picked all arrival times, predicted and observed slownesses can be calculated. To obtain the "observed" slowness, we use the measured time delays (relative arrival times) and perform a least squares fit of a plane wave to these observations. For comparison, the automatic beampacking results are also shown.

An important observation is the consistency in time delays. Tables 3.3 and 3.4 show the measured time delays for single sensors within subarray 04C and for each subarray beam respectively for the six events. All delays represents corrections to the theoretical arrival times where 01A00 (NAO) is normalized to zero.

In the above experiment, the theorectical arrival time is computed by plane wave delays for "observed slowness". This is to make the observations compatible with the data from Berteussen (1974). The important feature of the tables is the consistency in time delay corrections, even for events within this region where the signals are rather complex.

Conclusions

As can be seen from Tables 7.3.3 and 7.3.4, the measured time delay anomalies are very consistent even though one of the six events is located 500 km away from the others. This confirms the observations by Berteussen (1974) and also confirms that our correlation procedure performs well. Plans are now to begin analyzing a larger data base and integrate it with Berteussen's data in order to develop the best achievable beam deployment for NORSAR.

We might add that the establishment of systematic time delay anomalies is important for earth structure studies, and the data base will be made available to other researchers for this purpose. Also, the associated amplitude patterns, which will be compiled as part of this project, would be of considerable interest in studies of signal focusing and sources of scattering in magnitude observations, both at teleseismic and regional distances.

J. Fyen

Reeferences

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

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

#	Source	Origin time	Lat.	Long.	Depth	mb,ms	Comment
10	USGS	1995-110:08.45.04.100	6.495	126.580	33.0	6.1,6.1	Reviewed
10	IDC	1995-110:08.45.12.4	6.330	126.960	88.6	5.7	N 20
10	nao	1995-110:08.45.25.9	10.918	125.412	33.0	6.1	Analyst
10	nao	1995-110:08.45.39.293	12.038	122.008	33.0	6.0	EPX 213565
10	nao	1995-110:08.46.13.086	17.199	116.385	33.0	5.8	EPX 213570
10	nao	1995-110:08.46.13.7	17.165	116.397	33.0	5.8	C057
20	USGS	1995-111:00.09.55.810	11.977	125.634	33.0	5.9,7.0	Reviewed
20	IDC	1995-111:00.09.56.0	11.980	125.740	18.4	5.6	N 20
20	nao	1995-111:00.09.30.149	8.027	130.944	33.0	6.3	214480,anal
20	nao	1995-111:00.23.03.8	7.918	131.052	33.0	6.7	C057
30	USGS	1995-111:00.34.47.820	12.149	125.641	33.0	6.1,7.3	Reviewed
30	IDC	1995-111:00.34.44.6	12.060	125.520	0.0	5.8	N 17
30	nao	1995-111:00.34.23.0	7.902	129.340	33.0	6.6	Analyst
30	nao	1995-111:00.34.14.866	4.721	129.377	33.0	7.2	214625
30	nao	1995-111:00.47.55.1	17.979	118.007	33.0	6.0	C057
40	USGS	1995-111:00.30.12.840	11.883	125.574	33.0	6.2	Reviewed
40	IDC	1995-111:00.30.10.3	11.920	125.590	0.0	5.5	N 18
40	nao	1995-111:00.30.09.3	10.918	125.412	33.0	6.0	Analyst
40	nao	1995-111:00.30.22.811	12.162	121.918	33.0	6.5	214545
40	nao	1995-111:00.30.21.6	11.957	122.079	33.0	6.5	C057
50	USGS	1995-111:05.17.03.850	12.242	126.279	33.0	5.6,6.8	Reviewed
50	IDC	1995-111:05.16.59.0	12.060	125.720	0.0	5.6	N 16
50	nao	1995-111:05.17.43.0	16.198	115.652	33.0	4.7	215280 anal
50	nao	1995-111:05.17.07.247	13.366	131.432	33.0	5.9	215275
50	nao	1995-111:05.17.54.2	16.284	115.627	33.0	5.2	C057
60	USGS	1995-113:05.08.02.960	12.330	125.455	33.0	5.9,6.5	Reviewed
60	nao	1995-113:05.08.09.636	12.162	121.918	33.0	5.9	218775 anal
60	nao	1995-113:05.08.10.5	11.957	122.079	33.0	5.9	C057

Table 7.3.1. List of events.

#	Fkx	Onset time	v_C	v_O	v_B	ρ_C	ρ_O	ρ_B
10	213565	110:08.58.28.900	24.695	25.199	21.3	64.269	72.919	68.7
20	214480	111:00.22.56.346	24.005	26.064	21.3	62.681	69.193	67.5
30	214625	111:00.47.47.649	23.987	26.638	21.4	62.599	66.544	65.9
40	214545	111:00.43.13.613	24.011	25.432	22.3	62.775	72.599	69.2
50	218275	111:05.30.04.644	24.010	26.153	20.7	61.999	70.526	71.2
60	218775	113:05.21.01.727	23.958	26.133	20.0	62.681	69.783	70.3

Table 7.3.2. Estimated slowness components for different processes. v_C is apparent velocity predicted using IASPEI91 tables. v_O is apparent velocity estimated by plane wave least squares fit to measured time delays. The time delays are measured by using the interactive tool to pick each individual arrival time. v_B is apparent velocity estimated by beampacking process, including old time delay corrections. ρ_C, ρ_O, ρ_B are correspondingly the backazimuth components.

Epx	04C00	04C01	04C02	04C03	04C04	04C05
10	0.553	0.639	0.507	0.474	0.489	0.569
20	0.565	0.625	0.499	0.434	0.484	0.574
30	0.582	0.681	0.554	0.485	0.534	0.627
40	0.573	0.649	0.538	0.457	0.522	0.592
50	0.588	0.647	0.581	0.493	0.531	0.608
60	0.567	0.653	0.520	0.487	0.531	0.582

Table 7.3.3. Example of time delay corrections relative to the theorectical arrivals for sensors within subarray 04C.

Epx	01A_N	01B_N	02B_N	02C_N	03C_N	04C_N
10	0.000	-0.001	0.138	0.150	0.415	0.553
20	0.000	0.024	0.201	0.120	0.384	0.559
30	0.000	-0.001	0.200	0.073	0.366	0.582
40	0.000	0.004	0.167	0.106	0.393	0.573
50	0.000	-0.016	0.185	0.139	0.361	0.540
60	0.000	0.033	0.235	0.098	0.339	0.538

Table 7.3.4. Observed time delay corrections relative to the theoretical arrivals for subarray beams.

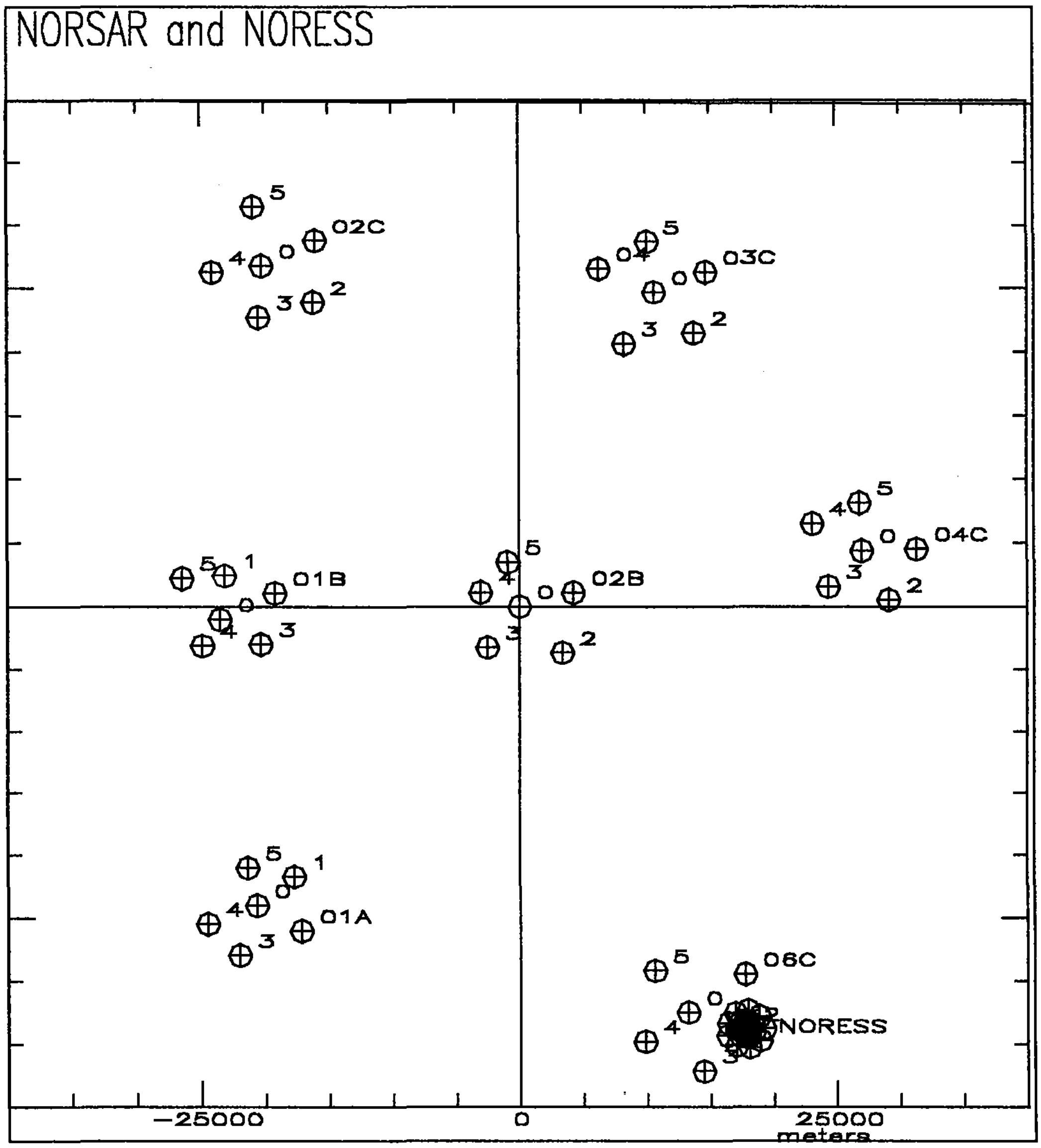

Fig. 7.3.1. Configuration of the large aperture array NORSAR and small aperture array NORESS. The NORESS array is co-located with the NORSAR subarray 06C. The diameter of NORSAR is about 60 km and the diameter of NORESS is about 3 km. Each instrument site is marked with a circle and a cross.

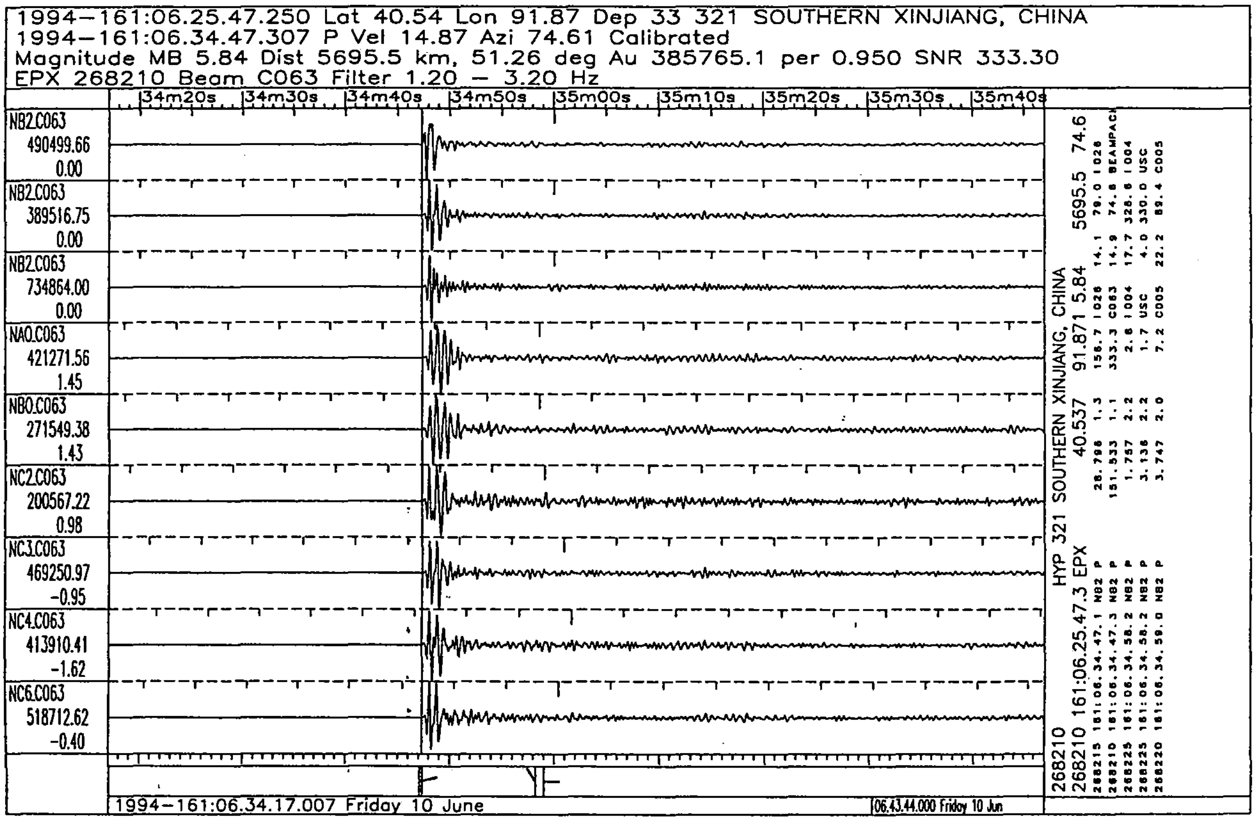

Fig. 7.3.2. Plot of automatic NORSAR detection/event processor output for the Lop Nor nuclear explosion of 10 June 1994.

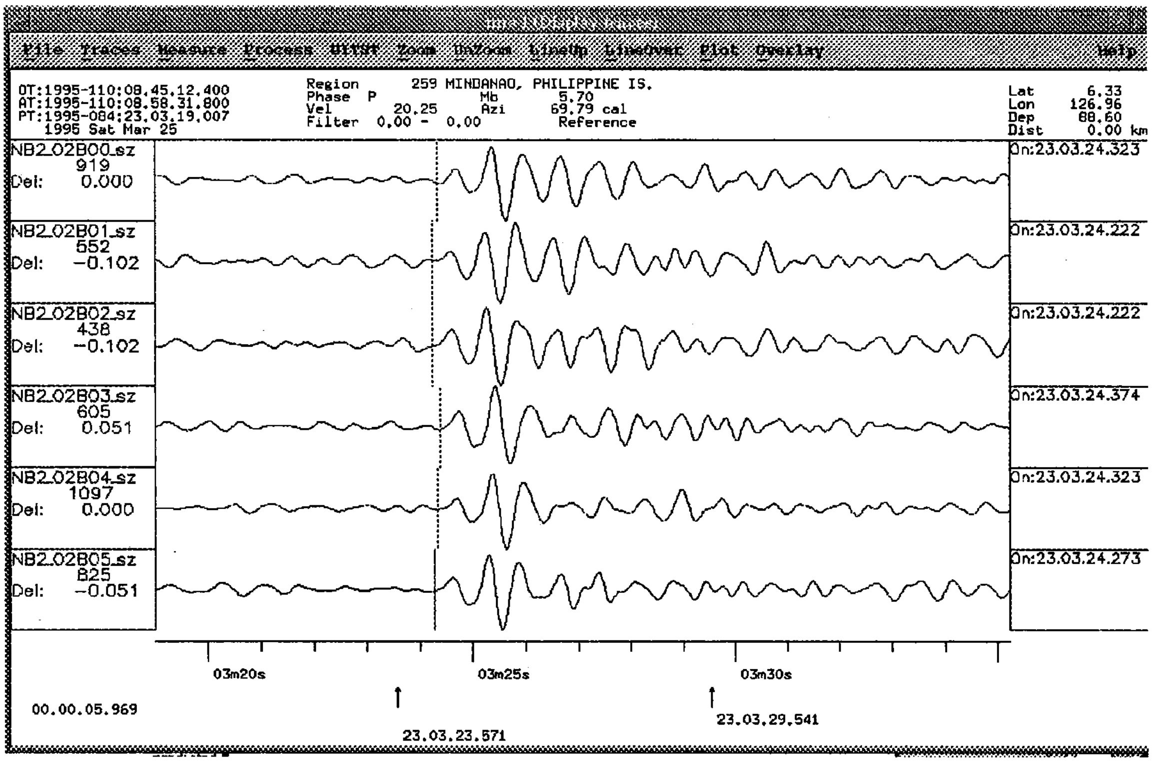

Fig. 7.3.3. NORSAR interactive tool for time picks. A trace-cursor containing the reference trace with reference arrivaltime mark is available to the user, but not visible on this figure. Using this cursor, the analyst can easily correlate the signals to find best arrival time pick.

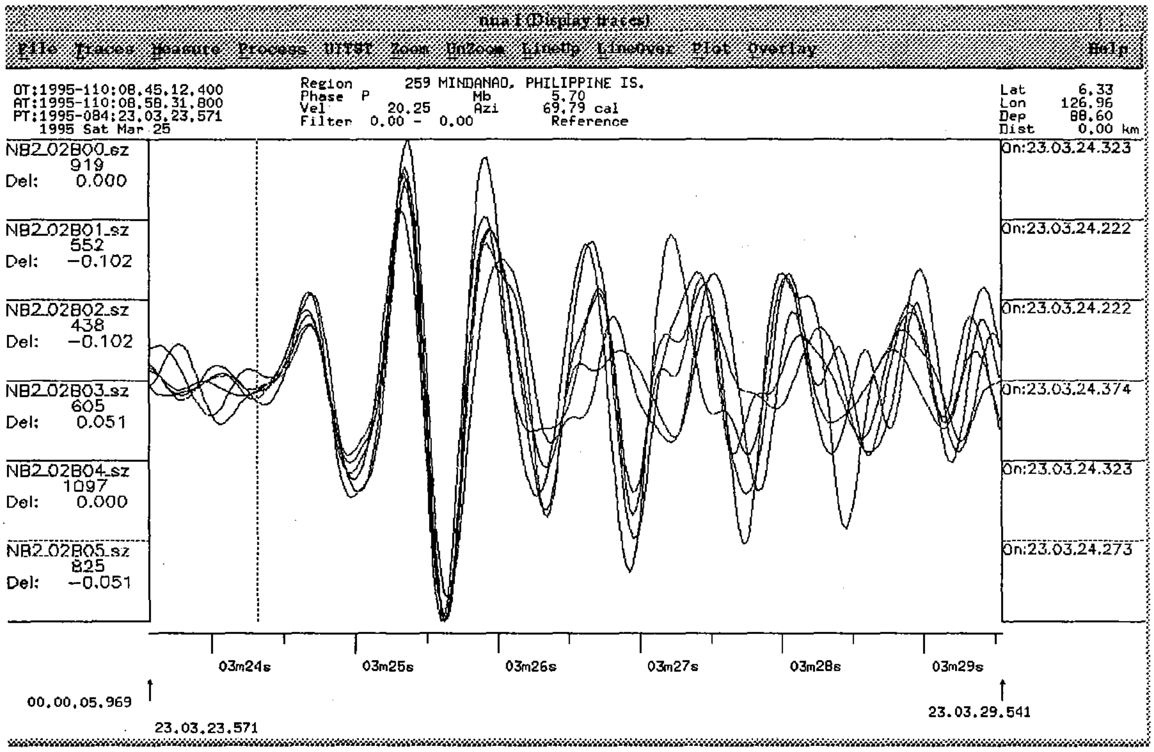

Fig. 7.3.4. Interactive tool for time delay measurements. A line-up of traces with respect to picked arrival time, overlay of the traces, and zooming can be used to check the similarity of the traces, and determine quality of the time picks.