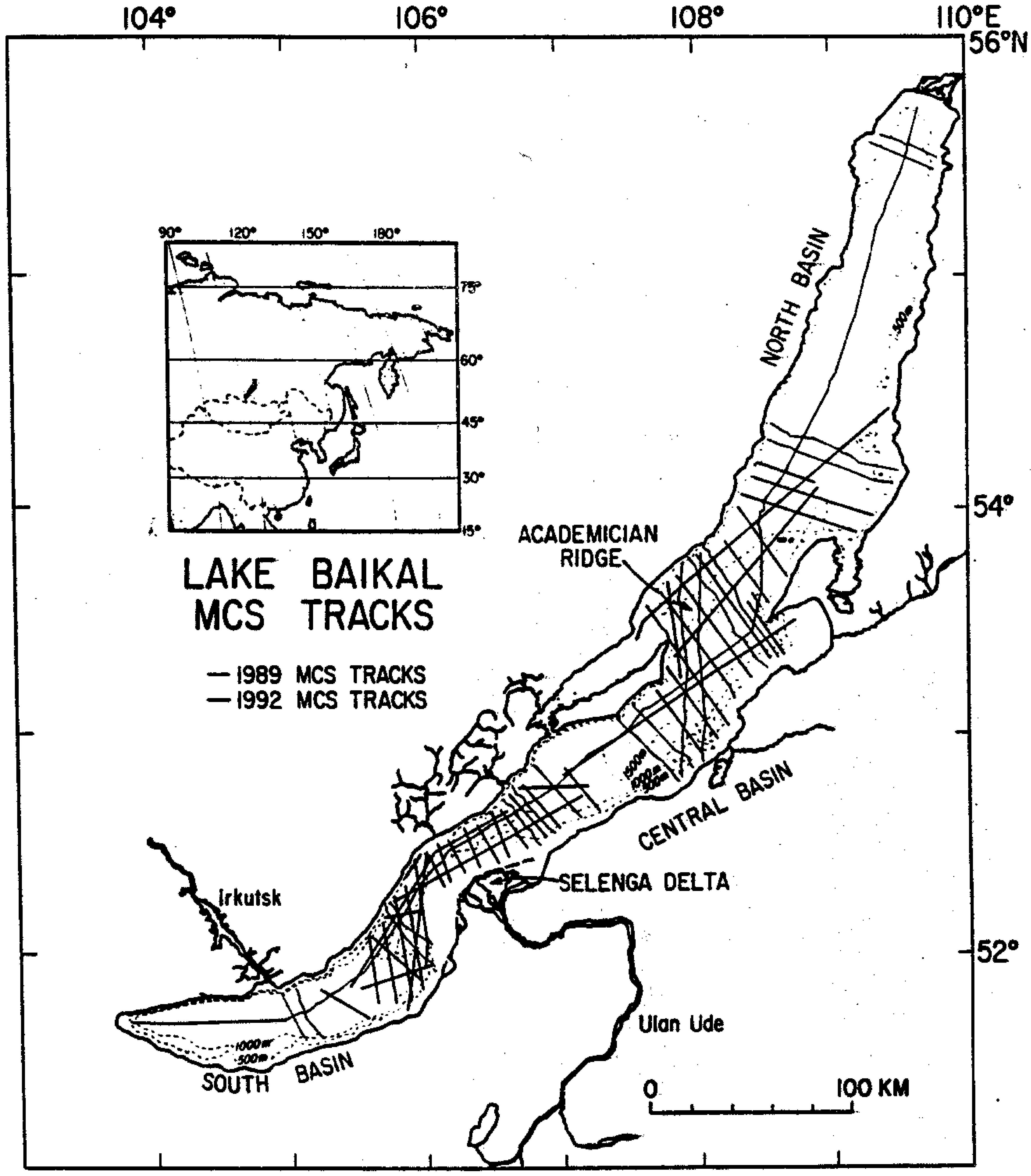
NAVIGATION QUALITY
FROM LAKE BAIKAL 1992 MULTICHANNEL SEISMICS CRUISE



by

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Open-File Report #95-233

1995

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INTRODUCTION

In August-September, 1992, a comprehensive multichannel seismic-reflection survey was conducted in Lake Baikal, Siberia (Figure 1), by U.S. and Russian scientists (Klitgord et al., 1993). Navigation utilized U.S.-supplied Global Positioning Satellite (GPS) receivers. Pre-cruise uncertainty in the availability and quality of the GPS positions at Lake Baikal together with limitations in both the ships layout and the navigation software resulted in (a) the seismic source being fired by increments of time rather than increments of distance and (b) navigation being acquired independently of the multichannel shot data. Because the navigation and multichannel data were not linked, the challenge in processing the shot point data was to assign an accurate time to each shot so that its position could be estimated from the raw navigation data.

The purpose of this report is to describe how times for each shot were derived, to describe how the positions were established for each shot number; and to assign a quality factor to the navigation for each line. The implications of these results for the geometry and processing of the multichannel seismic data are also discussed. This report complements other reports about the scientific objectives and operations of the cruise (Klitgord et al., 1993; Nichols et al., 1992) and the processing of the multichannel seismic profiles (Agena et al., 1994).

ACKNOWLEDGEMENTS

The success of the field program is due to the combined efforts of Russian and American scientists who participated in the R/V Balkhash multichannel cruise (Klitgord et al., 1993). I thank Warren Agena for his detailed accounting of missed shots based on observers logs and processing experience, Chris Schneider for developing the initial Matlab routines for displaying the navigation information, and Chuck Denham for advice and guidance in developing subsequent Matlab routines. Discussions with Barry Irwin, Uri ten Brink, and Chris Schneider helped focus many of the analyses presented here. Constructive reviews by Barry Irwin and Dave Foster are appreciated.

CRUISE SUMMARY

Approximately 2,250 km of multichannel seismic profiles were collected aboard R/V Balkhash in Lake Baikal in 1992 (Figure 1). Line numbers were assigned based on whether the lines were dip lines across the lake (even numbers) or tie lines along the lake (odd numbers). Because unequal numbers of dip and tie lines were shot, the line numbers are not sequential. There are 42 separate lines with numbers which range from 1 to 60. An additional 6 segments comprise reshot lines (3A, 10A, 17A, 40A, 50A, and 50B). Hence there are a total of 48 line segments for purposes of processing. The reshot lines have been given numerical designations of 61 - 66 (Table 1) for the purposes of navigation processing in this report but should otherwise be labelled by their A and B names officially, as shown on Plate 1. Line 17A (66) is a reshoot of line 17 with large-volume air guns and a slower firing rate (120 seconds) because of coincident recording of Ocean Bottom Seismometer data (ten Brink et al., 1993). The other A and B lines were reshot because of acquisition or navigation errors and are continuations of the original lines.

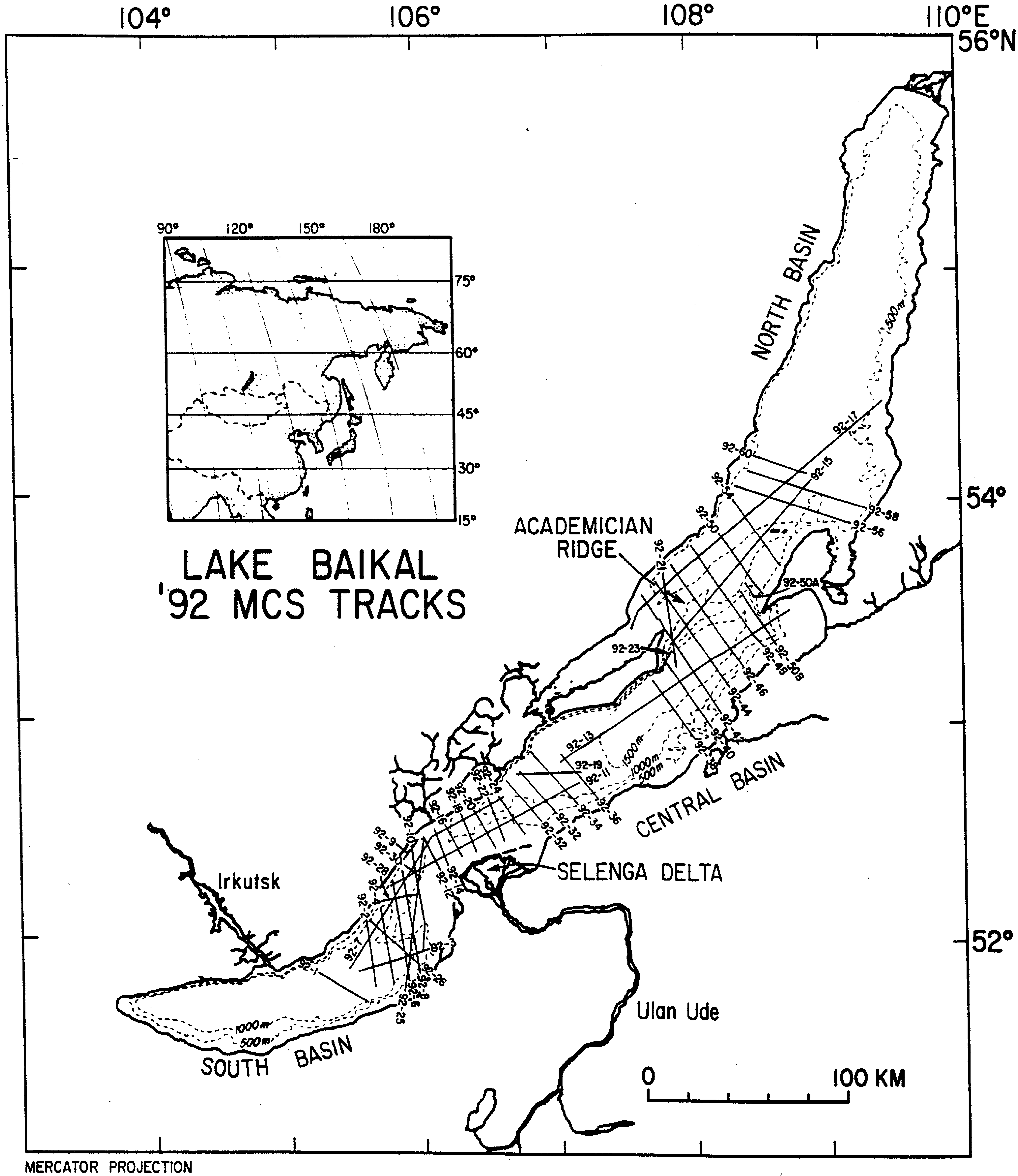

Figure 1. Map of Lake Baikal showing locations of 1992 multichannel seismic reflection lines. Detailed shot point map shown with locations of shot-time calibration points is shown at 1:1,000,000 in Plate 1.

TABLE 1: MULTICHANNEL SEISMIC LINES

LINE NO.	START OF LINE			END OF LINE			SHOT STATISTICS				
	SP	LATITUDE (°N)	LONGITUDE (°E)	SP	LATITUDE (°N)	LONGITUDE (°E)	SP	Pops	Dist. Between Shots Mean (m)	Std Dev.	Line Length (km)
1	1	51.839206	105.201489	559	51.708233	105.560494	559	559	52.84	6.0	29.485
2	1	51.783071	105.629929	633	52.087051	105.567371	633	645	54.47	10.9	35.079
3	1	51.850765	105.501235	357	51.899328	105.747565	357	363	49.47	5.2	17.908
4	1	52.149605	105.670043	785	51.782003	105.768467	785	787	54.83	13.9	43.096
6	1	51.816618	105.879697	989	52.266229	105.760121	989	1022	50.59	9.7	51.652
7	1	52.655717	106.592597	2430	51.865662	105.436463	2430	2430	50.74	7.7	123.247
8	1	52.314303	105.841174	1002	51.850539	105.962131	1002	1006	53.02	10.9	53.285
9	2	52.372973	105.862933	209	52.450676	105.945549	208	208	49.95	4.1	10.340
10	1	51.949527	105.987536	612	52.245438	105.955638	612	612	55.33	10.3	33.807
11	1	52.724903	107.152416	2137	52.250051	105.765371	2137	2195	50.03	5.8	109.766
12	1	52.470314	105.999674	389	52.324830	106.121876	389	389	47.86	8.6	18.570
13	1	53.501725	108.722460	2589	52.816525	107.016191	2589	2659	51.71	2.6	137.445
14	1	52.345429	106.177321	445	52.513714	106.077755	445	445	45.37	5.8	20.144
15	1	53.345518	107.837772	2055	54.083430	108.898227	2055	2118	51.06	4.0	108.094
16	1	52.524974	106.159986	375	52.388299	106.283627	375	375	46.74	3.9	17.481
17	4	53.416305	107.550809	3269	54.431400	109.430187	3266	3436	49.22	7.0	169.071
18	1	52.407923	106.389771	419	52.578701	106.276368	419	419	49.45	9.9	20.670
19	1	52.758528	106.685358	614	52.766729	107.166990	614	630	52.21	5.9	32.840
20	1	52.590038	106.377202	412	52.430051	106.531345	412	412	50.76	4.9	20.862

LINE NO.	START OF LINE			END OF LINE			SHOT STATISTICS				
	SP	LATITUDE (°N)	LONGITUDE (°E)	SP	LATITUDE (°N)	LONGITUDE (°E)	SP	Pops	Dist. Between Shots Mean (m)	Std. Dev.	Line Length (km)
21	1	53.666790	107.792267	839	53.254498	107.878360	839	839	55.93	10.2	46.869
22	7	52.461649	106.594541	447	52.654641	106.479988	441	441	52.49	8.3	23.096
23	1	53.225797	107.757865	214	53.311948	107.841735	214	214	52.21	3.6	11.121
24	6	52.659662	106.548910	468	52.488094	106.745470	463	463	50.87	5.6	23.502
25	1	52.470035	106.005250	1512	51.762643	105.854083	1512	1556	51.57	8.7	80.191
26	1	51.882724	105.956704	682	52.093360	105.576536	682	682	53.26	19.8	36.270
28	1	52.176104	105.679094	422	52.210791	105.959195	422	422	47.06	6.4	19.812
30	1	52.289463	105.978557	174	52.340680	105.859931	174	174	57.32	5.3	9.916
32	1	52.768784	106.717048	515	52.587911	106.976466	515	527	51.35	5.8	27.010
34	1	52.625482	107.138108	680	52.862889	106.797984	680	698	50.98	8.5	35.533
36	1	52.849071	107.015833	525	52.654255	107.283796	525	539	53.18	8.2	28.611
38	3	52.916477	108.017082	727	53.189930	107.698680	725	731	50.97	2.1	37.208
40	2	53.315349	107.782646	287	53.191747	107.888803	286	288	56.18	11.5	16.124
42	1	53.046122	108.212854	1321	53.567374	107.624293	1321	1341	52.74	4.3	70.672
44	1	53.626773	107.728682	1202	53.163772	108.271862	1202	1236	51.08	4.8	63.084
46	1	53.251909	108.376278	1180	53.700307	107.846792	1180	1180	51.93	2.7	61.225
48	2	53.342660	108.521755	1110	53.787435	108.004875	1109	1109	54.45	5.2	60.331
50	1	53.846333	108.207274	680	53.576083	108.526617	680	680	54.27	5.6	36.849
52	1	52.557162	106.860806	495	52.729505	106.616085	495	507	50.81	6.9	25.710
54	1	53.998034	108.311406	780	53.703211	108.658397	780	796	50.49	3.7	40.140
56	1	53.891457	109.172858	1143	54.053549	108.329005	1143	1167	50.16	3.3	58.487

LINE NO.	START OF LINE			END OF LINE			SHOT STATISTICS				
	SP	LATITUDE (°N)	LONGITUDE (°E)	SP	LATITUDE (°N)	LONGITUDE (°E)	SP	Pops	Dist. Between Shots Mean (m)	Std. Dev.	Line Length (km)
58	1	54.121276	108.429194	1138	53.956364	109.289270	1138	1162	51.16	3.3	59.397
60	1	54.110166	108.862215	545	54.194447	108.439032	545	557	52.66	3.6	29.279
10A/61	268	52.068757	105.999804	1082	52.421716	105.909836	815	815	49.49	8.4	40.285
3A/62	1	51.885350	105.679694	495	51.957939	106.033833	495	495	53.33	10.8	26.345
40A/63	241	53.216284	107.860166	860	52.977236	108.135716	620	620	52.46	2.7	32.473
50A/64	1	53.566630	108.459289	148	53.624164	108.402982	148	148	50.51	1.9	7.425
50B/65	1	53.583966	108.369064	635	53.347888	108.635654	635	635	50.15	3.1	31.795
17A/66	1	54.434425	109.436135	641	53.455028	107.572144	641	641	257.15	25.7	164.576

FIELD PROCEDURES

Navigation Logging

Navigation data were taken from an Ashtech GPS Model XII Receiver, using frequency band L-1 (1575 MHz) and signal modulation code C/A. The Ashtech antenna was located on a cross tree above ship's bridge. Every 10 seconds, navigation information was transmitted through an RS-232 port to a personal computer for logging. Logged data consisted of date, time, latitude, longitude, ellipsoidal altitude, Horizontal Dilution of Precision (HDOP) value, speed, and heading. No raw GPS signal information was saved from the multichannel tracks. The personal computer also provided real time displays for use in navigating the ship, such as distance along line, distance off track, distance and time to next way point, etc. Archive media for the navigation data were floppy disks from the portable computer.

Multichannel Shot Logging

The multichannel seismic acquisition system consisted of a Texas Instruments DFS V computer with dual 1600-bpi tape drives. A Digital Timing Delay Generator, i.e., a calibrated digital clock, issued a master trigger to the DFS V which initiated the firing pulse to the air gun array. The desired shot interval of 50 m was approximated by matching the time between shots with averaged ship's speed. Shots were generally fired every 23 to 25 seconds corresponding to a ship's speed of 4.0 to 4.4 kts, although some lines had shot intervals as low as 22 s and as high as 27 s. Firing rates were generally not varied within single lines.

Individual shot numbers were logged as the record or file number written onto the DFS V tape drive. Shot numbers for this cruise are therefore exactly equivalent to Field File Identification (FFID) numbers used in processing the multichannel data.

Calibration of Navigation and Shot Numbers

The shot numbers were calibrated to the navigation data manually at 15-minute intervals. The navigation watch stander logged the DFS V file number as an entry in the hand-written navigation log at 15-minute increments (about 35 to 40 shots). These entries were later typed as date-time-shot number files for processing the navigation, and are called shot-time calibration files.

SOURCES AND MAGNITUDE OF NAVIGATION ERROR

Three sources of error contribute to uncertainty in the Baikal navigation: (1) measurement limitation, (2) shot-time calibration, and (3) missing shots.

Measurement Limitation

This is error inherent in the hardware, software, and geometry of the GPS satellite and receiver system. The most variable source of error comes from the geometry of the satellites used in calculating the navigation position, and is referred to as the Dilution of Precision (DOP) factor (Milliken and Zoller, 1980; Hurn, 1989). DOP's are numerical values that can be recorded for 3-dimensional solutions (PDOP - Position Dilution of Precision), for 2-dimensional solutions (HDOP - Horizontal Dilution of Precision or VDOP - Vertical Dilution of Precision), and for time solutions (TDOP - Time Dilution of Precision). For the Baikal data, HDOP was recorded rather than PDOP because navigation solutions on a lake surface are essentially made at the same vertical elevation. This also allowed for 3-satellite solutions to be used if 4-satellite solutions were not available. HDOP values for good satellite geometries are generally between 1 and 4; values for poor geometry are much larger.

Other sources of measurement error are generally constant and are summarized below (Table 2):

TABLE 2: Typical Sources of Measurement Error[1]

SOURCE	ERROR (M)	DESCRIPTION
Satellite Clock	.6	Clock Drift
Ephemeris	.6	Uncertainty in satellite orbit
Receiver	1.2	Clock synchronization with satellite
Atmospheric/Ionospheric Effect	3.7	Signal propagation delays
Selective Availability[2]	0 - 7.6	Random signal degradation
Root-Square Sum[3]	4 - 9	Estimated Combined Error
Baikal estimate	**7**	**Assumed mid-value**

[1] Source: Hurn (1989).
[2] Selective Availability is unannounced degradation of the signal by Department of Defense. This is the most unconstrained source of error. 7.6 m is considered worst case.
[3] Root-Square Sum is the square root of the sum of the squares.

Total measurement error is calculated by taking the product of the HDOP value with the root-square sum of the other sources of error (Hurn, 1989). For the Baikal data, a representative root-square sum value of 7 m is assumed. The measurment error in meters is therefore taken as 7 times HDOP.

Shot-Time Calibration

This refers to the logging of time and/or shot numbers at the 15-minute calibration points. The magnitude of this error is related to human error in logging time and and/or shot number correctly at the calibration points. Ideally, the clock used to fire the airgun array should have been synchronized to the GPS clock and shot-time recorded automatically to a fractional second. In actuality, the (GPS) times at calibration points were logged to whole seconds (best case) or whole minutes (worst case). Logging time in whole minutes was most common at the beginning of the cruise because of language difficulties between some of the Russian and American watch standers. Very few of these human errors occurred in the latter part of the cruise.

These errors in time are given values of 1 s (for whole second logging) and 30 s (for whole minute logging, assuming time is rounded to the nearest whole minute). To convert these errors in time to position error in meters, the mean distance between 10-s positions was either divided by 10 (to get mean distance for 1-s interval) or multiplied by 3 (to get mean distance for 30-s interval). The magnitude of the uncertainty due to the 1-s error is about 2 m; that for the 30-s case is about 70 m.

Shot-time errors could also occur if shot numbers were improperly logged. Occassionally, shots from the navigation log showed gross inconsistency with the multichannel observer's logs, indicating that the watch stander erroneously recorded the shot/file number. The more obvious errors could be corrected after comparison of the navigation logs with the multichannel observer's logs.

Missed Shots

This refers to situations in the field in which the airgun array continued firing at even increments of time even though the DFS V was not recording the shot or incrementing the file/shot number. The actual shot-time calibration points are based on the field file numbers from the DFS-V, rather than the actual firing of the airgun array, which means missed shots are not automatically counted. In the first half of the cruise, several poor quality tapes together with excessive parity errors on one of the tape drives resulted in missed shots. In the second half of the cruise, when only one tape drive was used, two firings were missed at every tape change because of the physical limitations in removing and reloading a single tape drive. For times in which missed shots occured, the navigation interpolation must include a correction for the additional shots that occurred in that interval.

In order to compensate for the missed shots, the concept of a "pop" number is introduced for the processing. The pop number differs from the shot number in that the pop increments every time the air-gun array fires whereas the shot number increments only when the DFS V writes a file to tape. Missed shots (i.e., those not recorded on the DFS V) will introduce a systematic offset between the pop number and the shot number. Both pop and shot numbers should be identical for lines in which no recording errors (i.e., missed shots) occur. *The concept of the pop number for the Baikal data is used only in the processing of the navigation information and is not logged in any of the final archive navigation files.*

Figure 2 shows a hypothetical situation to emphasize the effects of poor logging and missed shots on estimating the time of each shot. Time is shown incrementing to the right, with a 15-minute calibration interval noted. (Assuming a constant ship's speed of 4.5 kts, this hypothetical time curve can also be equated with distance, or 15 minutes equals about 2.1 km). Suppose there are 15 shot numbers recorded from minute 1 to minute 15 (i.e., 15 files written on the DFS V). If there are no missing shots, then the shot number equals the pop number and configuration A holds for interpolating 15 even intervals for the shot times. However, if there are 5 missed shots (shown as *), then the pop number exceeds the shot number by 5 and configuration B (20 even time intervals) is the accurate representation for determining the shot times. If the missed shots are not accurately accounted for, then the shot time will be correct at the calibration points (shots 0 and 15), but will be misestimated (by up to 2.25 minutes for shot 6). This timing error for shot 6 equals a distance mislocation of 313 m in this example. In general, this error is greatest at the position of the missing shots and decreases toward the 15-minute calibration points.

If the time is not logged properly for the 15-minute calibration, then a shot-time calibration error is introduced. For whole minute logging, the timing error is assumed to be 30 s (i.e., watch stander recorded the whole minute to the *nearest* whole minute). The effect on estimating shot time is shown by configuration C in Figure 2, where one scenario is illustrated in which the whole minutes reported are considered to be off by 30 seconds at each calibration

Figure 2. Three scenarios for estimating shot times in a fifteen minute interval from shot-time calibration files. For simplicity, one shot per minute is assumed. Shot points are shown by open circles; missing shots (i.e., when the airgun array fired, but no file was recorded on the DFS V) are shown by *. The first and last point for each of the three configurations is the logged calibration point at minute 1 and minute 15. (A). No errors: In this case, the two calibration points at minutes 1 and 15 are used to interpolate 15 shots, or a shot at each minute. Shot number 5 (filled circle) corresponds to minute 5.0. (B). Missing Shots: In this case, five missing shots (*) occur between shot 5 and 6. The corresponding pop number is shown beneath the row of shots. In this case, there are 20 shots in the calibration interval and shot 5 would be assigned a time of 4.0 minutes. (C) Whole Minute Logging: For this case, if the actual calibration shots occurred at minutes 1.5 and 15.5 (i.e., 30 seconds after the minute), then the times *should be calculated* as shown here. Shot 5 occurs at 5.5 minutes. However, if whole minute logging was done, the shots would be calculated similar to case A.

point. Configuration C shows what the actual shot times should have been; configuration A shows how they would be calculated in the absence of the seconds information. In this case, the calibration shots 0 and 15 would have an error of 30 seconds (69 m), as would all shots in that interval.

The missing-shot error is actually treated as a correction to the data rather than as an error; i.e., missing shots are accounted for in the processing, but no missing-shot error is calculated or assigned. This assumes that the missing shots were reasonably carefully logged and that any unlogged shots are not enough to bias an entire line. Most of the missing shots compensated in the processing are single or double shots (representing a timing correction of up to 45 s at the position of the missed shots, or up to about 100-m correction). The most missing shots that occurred at one interval are 17 on line 6. One or two missed shots generally has no visible effect on fold coverage of the multichannel data. However, the 17-shot gap in line 6 was sufficient to cause a small data gap at SP 820-821.

PROCESSING STRATEGY

Two basic inputs are used in processing the navigation: the raw 10-s locations and listings of the shot-time calibrations points. The steps in processing the navigation data (Figure 3) were:

(1) Inspect the overall quality of the raw navigation data by looking at gaps and calculating the distance between adjacent fixes for each 10-second recording point. Plot ellipsoidal height and HDOP value for general quality control.

(2) Evaluate the quality of the shot-time logging, which was done by calculating firing rate for each 15-minute calibration interval and inspecting the scatter. Ideally, with a constant firing rate of the airgun array, the recomputed firing times for each 15-minute period should also be constant, or vary slightly when the firing rate was infrequently adjusted for changes in the ship's speed.

(3) Edit the calibration files for obvious typographical errors based on the magnitude of the scatter observed in plots from step 2.

(4) Develop and merge the best estimates of the number and positions of missing shots with the calibration files. In this step, the pop numbers were defined.

(5) Generate final latitude/longitude positions by using the updated calibration files to interpolate times for each pop, which are then merged with the raw navigation files to interpolate latitude and longitude for the pop times. Final archive navigation drops the pop numbers which do not have accompanying shot numbers defined.

(6) Inspect the quality of the shot navigation by looking at the distance between adjacent pops for each line.

(7) Assign an error to each line based on the quality of the raw navigation and the errors introduced in the calibration files.

Plots showing the results of step 1 are given in Appendix 1 for each line. Plots resulting from steps 2, 4, 5, and 6, are given in Appendix 2 for each line.

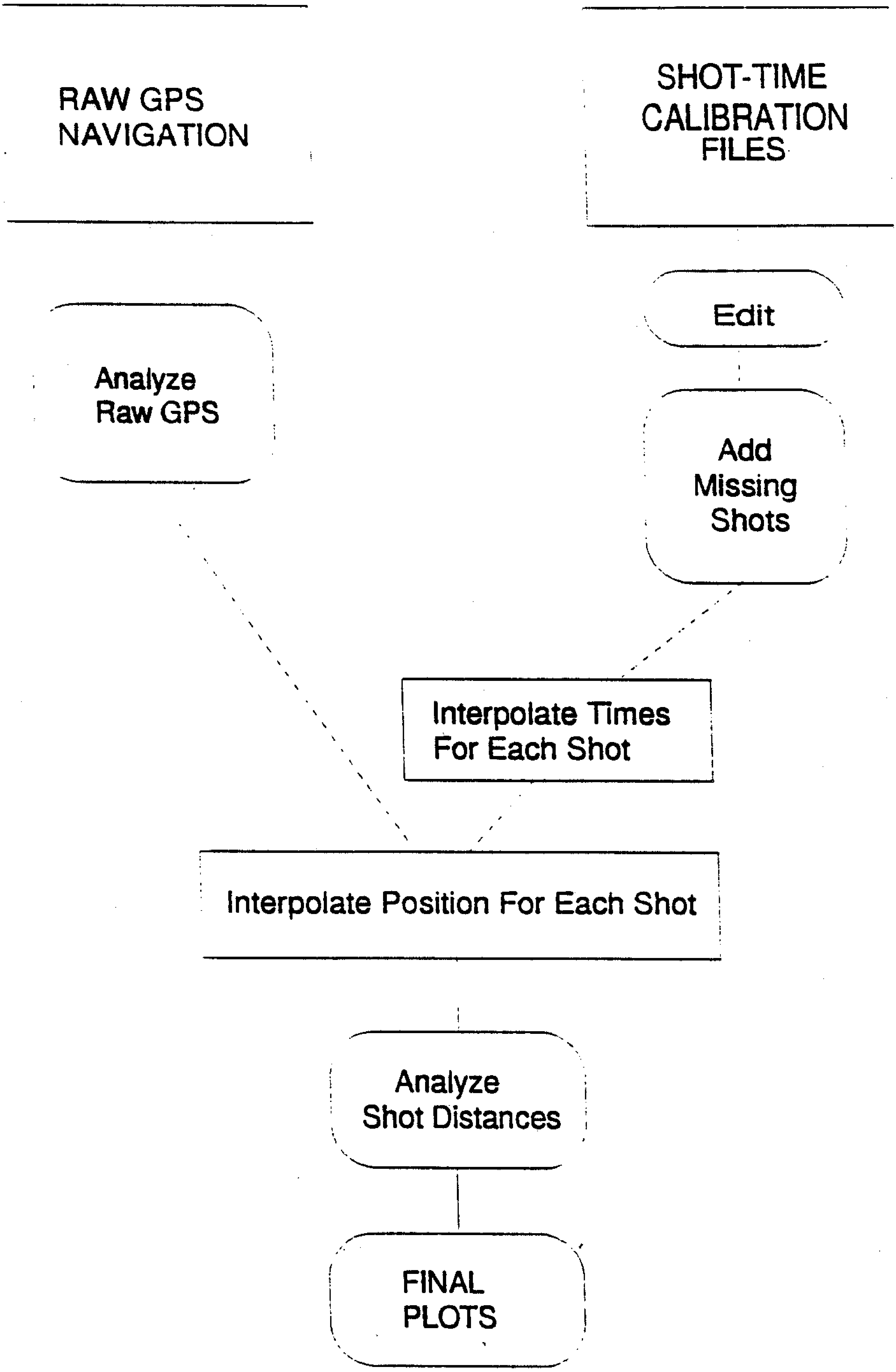

Figure 3. Flow chart of the navigation processing.

TABLE 3: DATA GAPS

Line No.	START OF GAP		END OF GAP		LENGTH (s)	SHOTS IN GAP	
	Date	Time	Date	Time		Total	SP Nos.
6	920826	175622	920826	180302	400	16	909-924
7	920829	190902	920829	191012	70	2	526-527
7	920829	191032	920829	191302	150	6	529-534
8	920826	233412	920826	233522	70	2	284-285
8	920827	011652	920827	012612	560	23	530-552
8	920827	012702	920827	013242	340	14	555-568
8	920827	024802	920827	025102	180	7	748-754
11	920922	195412	920922	195632	140	6	324-329
13	920920	225812	920920	230212	240	10	444-453
13	920920	234632	920920	235302	390	15	555-569
13	920921	035032	920921	035322	170	7	1107-1113
13	920921	035452	920921	035722	150	6	1117-1122
13	920921	065652	920921	070112	260	11	1543-1553
13	920921	121612	920921	121822	130	6	2353-2358
17	920916	050002	920916	054122	2480	108	2866-2973
26	920831	174122	920831	175132	610	25	148-172
34	920922	003132	920922	003432	180	6	509-514
38	920910	134342	920910	134642	180	7	700-706
46	920913	082032	920913	082432	240	10	22-31
46	920913	083642	920913	083802	80	3	63-65
50	920912	181132	920912	181232	60	2	236-237
50	920912	193252	920912	193352	60	2	432-433
52	920922	090112	920922	090232	80	4	58-61
66	920916	164852	920916	170832	1180	9	51-59
66	920917	112842	920917	113242	240	2	605-606

RESULTS

Quality of the Raw Navigation

Raw navigation information is illustrated in Appendix 1 with four plots for each line: distance between each data point (top plot), time between each data point (second plot), HDOP value associated with each data point (third plot), and ellipsoidal height (bottom plot).

The plots of distance between each point show considerable scatter on some lines (e.g., line 4, with a standard deviation of 13.6 m) and remarkably little scatter on others (lines 23, with a standard deviation of 1.44 m). The 10-s positions average about 20 - 23 m apart throughout the cruise, and the standard deviations range from about 5 % (line 23) to more than 50 % (line 4).

In general, the scatter is correlated to changes in HDOP value (e.g., HDOP changes rapidly on line 4 and is less variable for line 23). This correlation suggests that the scatter is best explained by changes in satellites and/or satellite geometry used in computing successive positions along a track line.

Because data points were logged every ten seconds, the plot of time between data points should be constant at 10 s. Deviations from this represent data gaps. Note that data gaps in time are duplicated as large peaks in distance between points (e.g., line 8 at 3.75 - 4.0 hours). Table 3 summarizes the data gaps for the 14 lines with gaps of 1 minute or more (i.e., 6 or more data points lost). The two largest gaps were on lines 17 and 17A, in which data losses occurred of 41.3 and 19.6 minutes respectively.

Measurement error can be estimated directly from the raw navigation. Table 4 lists the mean measurement error for each line. As defined earlier, the measurment error is given as 7 x HDOP, where HDOP is the mean HDOP calculated for each line. These errors range from 7.49 m (lines 42 and 52) to 22.75 m (line 40). Figure 4 (top plot) illustrates these errors, shown as X's together with estimates of the scatter (standard deviation of the calculated distance between data points), shown as O's. In general, the two values are in good agreement. The error bars are the standard deviation of the error, and are primarily an indicator of the amount of scatter in the HDOP value.

Quality of the Calibration Files

Plots of the initial and final calibration files are shown as the upper two plots in the figures in Appendix 2. The calibration curves are displayed as firing rates, calculated by dividing the time between control points by the number of shots between control points. The control points plotted in the edited (final) version use pops between control points to calculate the shot interval, although the information is plotted against shot numbers. Ideally, these lines should be constant and horizontal along the line, because the pops were fired by time, or they should show a small offset where the shot number may have been adjusted for small changes in the speed of the ship.

All of the plots of the initial calibration files show a boxy pattern, in which the shot interval varies between high (24 - 27 s) and low (21 - 23 s) values. This is a direct result of poor record keeping and missing shots. After editing, some of the lines have excellent (i.e., flat) curves (e.g., lines 54 and 58). Many of the lines show considerable improvement in the flatness of the calibration curves after editing (e.g., lines 11 and 13) whereas a few show little or no improvement (e.g., line 15). The final calibration curves have been assigned a rating of 1 (time logged to whole seconds) or 30 (time logged to whole minutes); these values are listed in Table 4, together with the calculated error in distance that these timing errors correspond to.

Lines in which some or all of the calibration points were logged to whole minutes were given ratings of 30, even if the final curves looked reasonable, because of the absolute uncertainty in shot time based on the poor time-keeping, as described with Figure 2. For example, line 6 is given a 30-s error value for the entire line even though whole minute logging occurred only in the first half of the line. Line 7, one of the long tie lines across the Selenga Delta, contains whole-minute logging for only about 25 % of the line (600 shots from about SP 1000 - 1600), but is also assigned a 30-s error for the whole line. The portions of lines which had whole-minute logging are clearly marked in Appendix 2, and should be inspected to clarify how much of any line is affected by the whole-minute logging.

The shot-time calibration error was combined with the measurement error using a root-square sum to yield total error for each line. Figure 4B shows the total error (i.e., for both measurement and shot-calibration errors). A comparison of this figure with the measurement error (Figure 4A) reveals the large contribution of the shot-time calibration error due to the whole-minute logging (30-s error). For example, line 4, which has a measurement error of 8.89 m, has a combined total error of about 74 m when the shot-time calibration is added. The difference between the measurement error and the total error for lines with a 1-s shot-time calibration error is generally negligible.

Quality of the Distance Between Shots

The quality of both the raw navigation and the calibration files affects the calculations of distances between shots. These distances are shown in two forms in Appendix 2 (lower two plots): as relative distance between shots along each line (third plot down) and a histogram of distances (lowest plot). The plot of distance between shots gives a good representation of the magnitude of the scatter along the line; the histogram illustrates the spread of the scatter. All plots are at the same scale for easy comparison. The standard deviations given on the plots are based on the relative distances between shots, rather than the uncertainty associated with the absolute position of the shot.

The scatter recorded for distances between shots essentially mirrors that of the raw navigation plots (compare plots for each line in Appendix 1 and Appendix 2). The distances between shots are important for evaluating the assumption of 50-m shots used to process the multichannel data. Figure 5 shows the mean distance between shots (X) together with the standard deviation (error bar) for each line. The ideal shot distance of 50 m is also shown as a horizontal line.

Except for line 30, the error bars encompass the 50-m ideal shot spacing. Hence the assumption of 50-m shots is valid for processing the data. Line 30 has a mean shot spacing of 57-m, but is a very short line (174 shots) and therefore is a very small element of the entire data set.

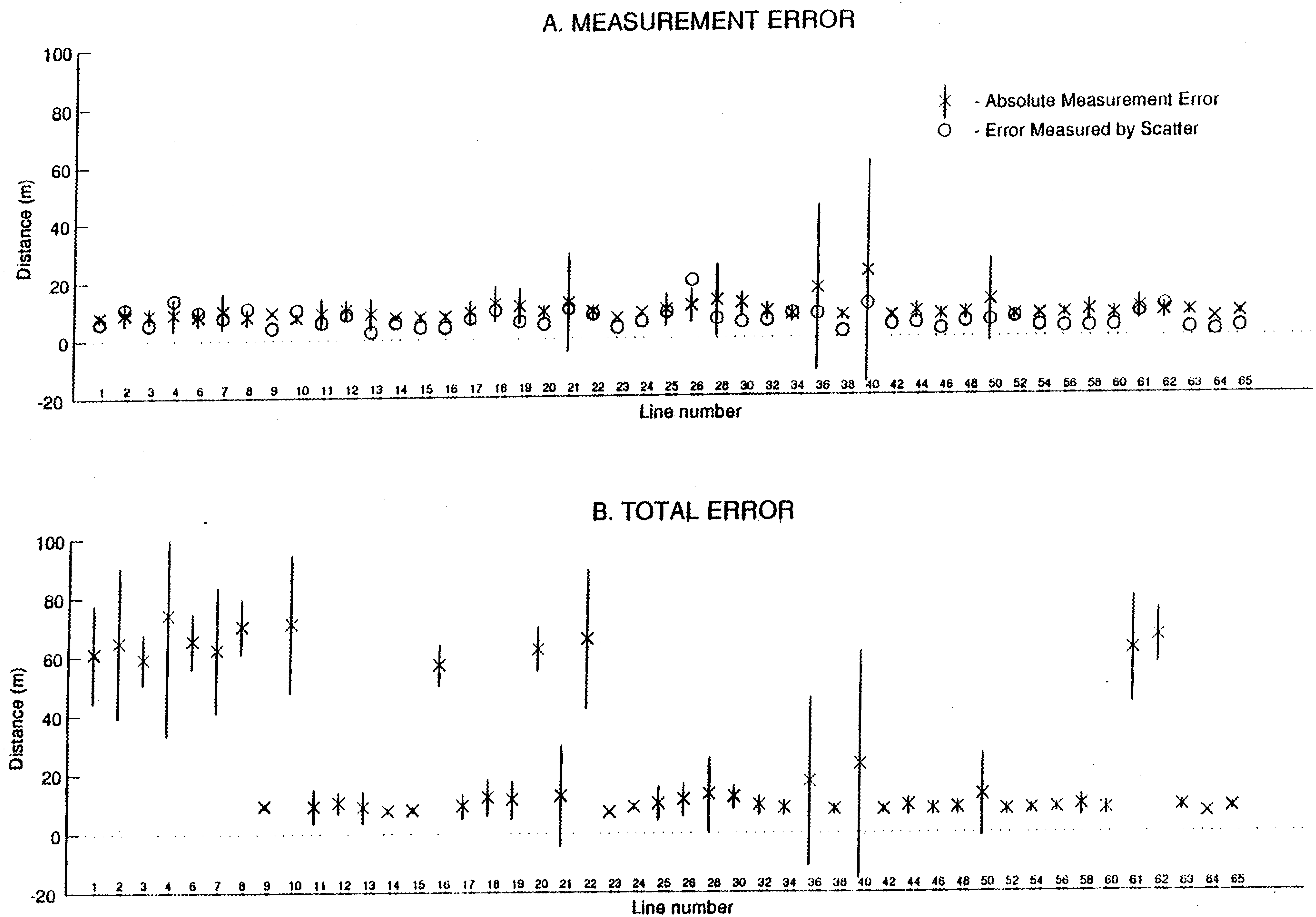

Figure 4. Plots of error. (A) Measurement error for each line (X) plotted with standard deviation (shown as the error bar). These measurement errors are also tabulated in Table 4. The standard deviation is primarily a reflection of the scatter in the HDOP values. The scatter in the distance between 10-s positions (O) is also plotted for each line and is generally consistent with the measurement error. A light dotted line is shown along the zero value. (B) Total error, given as the error due to both the measurement and shot-time calibration values. The difference between the measurement error (shown in the upper plot) and the total error (shown in the lower plot) is due to the contribution of the large shot-time calibration error for 13 lines.

TABLE 4: NAVIGATION ERROR AND DATA QUALITY

LINE NUMBER	MEAN SHOT DISTANCE[1]	MEASURE-MENT ERROR[2]	SHOT-TIME CALIB.		TOTAL ERROR[5]	RATING[6]
			Factor[3]	Error[4]		
1	52.84	7.98	30	60.51	61.03	Poor
2	54.47	9.17	30	64.14	64.79	Poor
3	49.47	8.68	30	58.50	59.14	Poor
4	54.83	8.89	30	73.68	74.21	Poor
6	50.59	8.33	30	64.83	65.36	Poor
7	50.74	10.15	30	61.50	62.33	Poor
8	53.02	8.05	30	69.84	70.30	Poor
9	49.95	9.38	1	2.01	9.59	Excellent
10	55.33	7.70	30	70.71	71.13	Poor
11	50.03	9.10	1	2.23	9.37	Excellent
12	47.86	10.43	1	1.99	10.62	Excellent
13	51.71	8.89	1	2.15	9.15	Excellent
14	45.37	7.63	1	1.85	7.85	Excellent
15	51.06	7.77	1	2.20	8.07	Excellent
16	46.74	7.84	30	56.40	56.94	Poor
17	49.22	9.31	1	2.28	9.58	Excellent
18	49.45	12.25	1	2.02	12.41	Good
19	52.21	11.27	1	2.27	11.50	Excellent
20	50.76	9.31	30	61.53	62.23	Poor
21	55.93	12.46	1	2.37	12.68	Good
22	52.49	9.31	30	64.89	65.55	Poor
23	52.21	6.93	1	2.09	7.24	Excellent
24	50.87	8.68	1	2.04	8.92	Excellent
25	51.57	9.80	1	2.27	10.06	Excellent
26	53.26	11.13	1	2.31	11.37	Excellent
28	47.06	12.95	1	1.93	13.09	Good
30	57.32	12.04	1	2.22	12.24	Good
32	51.35	9.17	1	2.19	9.43	Excellent
34	50.98	8.12	1	2.33	8.45	Excellent

36	53.18	17.08	1	2.39	17.25	Good
38	50.97	7.70	1	2.06	7.97	Excellent
40	56.18	22.75	1	2.28	22.86	Good
42	52.74	7.49	1	2.22	7.81	Excellent
44	51.08	8.96	1	2.08	9.20	Excellent
46	51.93	7.84	1	2.20	8.14	Excellent
48	54.45	8.33	1	2.21	8.62	Excellent
50	54.27	12.67	1	2.22	12.86	Good
52	50.81	7.49	1	2.19	7.80	Excellent
54	50.49	7.84	1	2.20	8.14	Excellent
56	50.16	8.19	1	2.18	8.47	Excellent
58	51.16	9.17	1	2.14	9.42	Excellent
60	52.66	7.84	1	2.22	8.15	Excellent
61/10A	49.49	10.01	30	60.90	61.72	Poor
62/3A	53.33	8.75	30	65.52	66.10	Poor
63/40A	52.46	8.68	1	2.20	8.95	Excellent
64/50A	50.51	6.37	1	2.02	6.68	Excellent
65/50B	50.15	8.12	1	2.17	8.40	Excellent
66/17A	257.15	8.61	1	2.19	8.88	Excellent

[1]Mean Shot Distance - Mean distance between successive firings of the airgun array after taking into account all missing shots. This same number is given in Appendix 2 on the top plot for each line.

[2]Measurment Error - Error due to inherent limitations of the satellite-receiver system. This number is taken to be 7 times mean HDOP, as discussed in the text.

[3]Shot-Time Calibration Factor - This is the factor assigned to each line based on the quality of the shot-time calibrations. 1 refers to times recorded to whole seconds; 30 is for times recorded to nearest whole minute.

[4]Shot-Time Calibration Error - This error is given as the average distance between 10-s navigation locations (top plot of Appendix 1) multiplied by .1 (1-s factor) or 3 (30-s factor).

[5]Total Error - Taken as the root-square sum of the measurement and shot-calibration errors.

[6]Rating - Excellent is for error of 6-12 m; Good is for errors of 12-24 m; Poor is for errors > 50 m.

Figure 5. Summary of estimated distances between shots for each line. The mean (X) and standard deviation (vertical bar) are shown with line number annotated beneath. The standard deviations are for relative distances between shots and do not reflect absolute accuracy of the navigation positions. Estimates of absolute accuracy are shown in Figure 6.

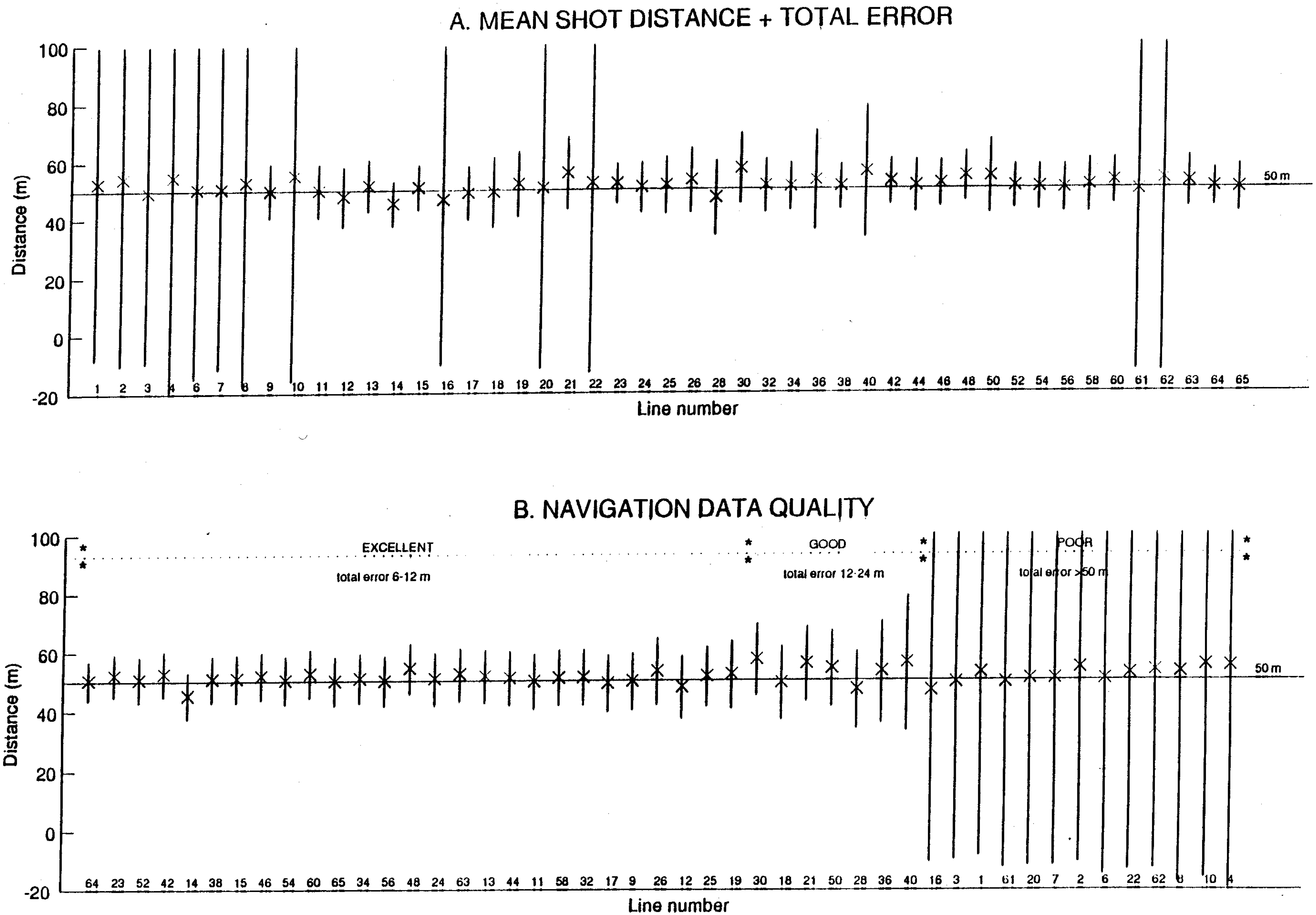

Figure 6. Summary of the total error and navigation quality associated with each line. (A) Total error plotted as an error bar around the mean distance between shots (X). The 50-m ideal shot spacing is shown as a horizontal line for reference. Error values are listed in Table 4. (B) Estimate of navigation quality using ratings of Excellent (for errors of 6-12 m), Good (for errors of 12-24 m), and Poor (for errors > 50 m).

Quality of Shot Locations

For the purposes of this report, an error estimate is assigned to each line based on the mean characteristics of the line (e.g., mean HDOP), rather than assigning an error estimate to each individual shot. This gives a general guide for interpreting the navigation quality for each multichannel profile.

Figure 6A gives the total position uncertainty for each line plotted as an error bar around the mean shot distance. The value of the error bar is taken as the total error (X) shown on Figure 4B and tabulated in Table 4. The lines with whole-minute logging of the shot-time calibration points are ovvious because of their large error bars (e.g., lines 1-8).

A quality rating has been assigned to each line based on the size of the total error and is illustrated in Figure 6B. The lines have been arranged in order of increasing error-bar size. Lines with error bars of 6-12 m are considered to have excellent navigation; those with error bars of 12-24 m (i.e., up to half a shot interval) are considered to have good navigation; and those with error bars in excess of 50 m (i.e., one shot interval) are considered to have poor navigation.

Line Crossings

Line crossing information has been compiled from the processed navigation locations for each multichannel line and is given in Appendix 3.

DISCUSSION

A map of the navigation quality rating of each line (Figure 7) shows that lines on the southern side of the Selenga Delta have the worst ("Poor") navigation whereas those around Academician Ridge have the best ("Excellent") navigation. The reason for this geographic distribution can be explained because the Selenga Delta survey was completed first, when the most communication problems and human error occured in logging.

In as much as the purpose of the cruise was to collect multichannel seismic data, a relevant issue is how the quality of the navigation data affects the multichannel data, specifically the multichannel geometry. The marine multichannel technique is based on repetition of regular geometries that allow sorting and reconstruction of common depth point seismic gathers for velocity analysis and stack (e.g., Yilmaz, 1987). Perturbations of this geometry, such as that which occurs when shots are not at the target 50-m spacing, introduce artifacts and complications in processing the data.

For the Baikal data, the shots were ideally 50-m apart to preserve the optimum geometry for recovering 24-fold data (Agena et al., 1994). The actual mean distance between shots ranged from 45 m (line 14) to 57 m (line 30). For all lines except line 30, the uncertainty (i.e., the scatter around the mean shot spacing) includes 50 m, and the assumption of 50-m firing intervals for processing the data is therefore within the estimated navigational uncertainty.

Because of the low frequencies used in the multichannel seismic survey (less than 60 Hz), velocity estimations will not be affected by using a geometry of 50-m firing intervals instead of the actual mean intervals of between 45 and 57 m. The region insonified on the lake floor by

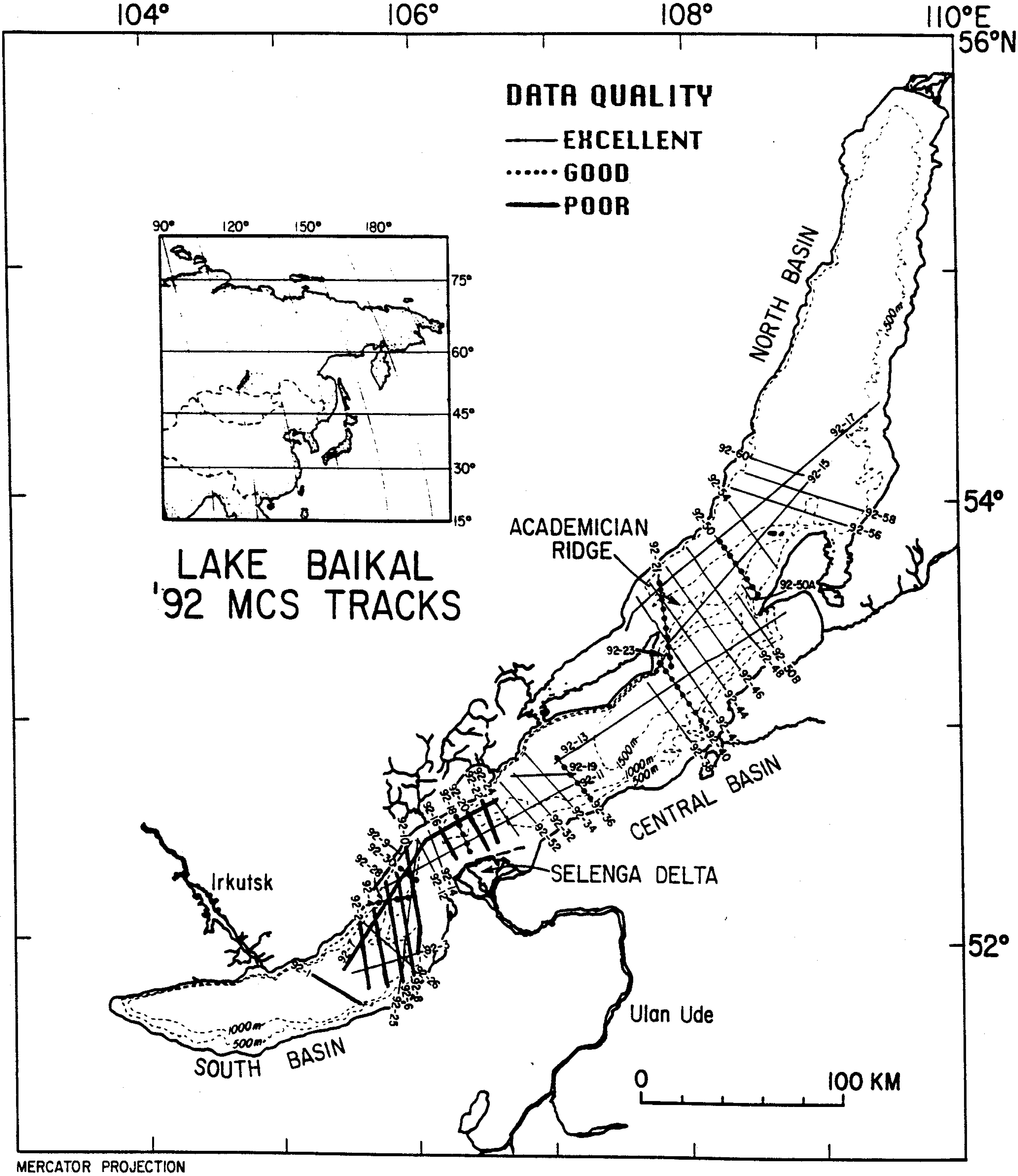

Figure 7. Map showing the distribution of the navigation quality for the lines in Lake Baikal. The lines with the lowest "Poor" rating are generally in the region of the south Selenga Delta, where shot-time calibration logging was poorest at the beginning of the cruise.

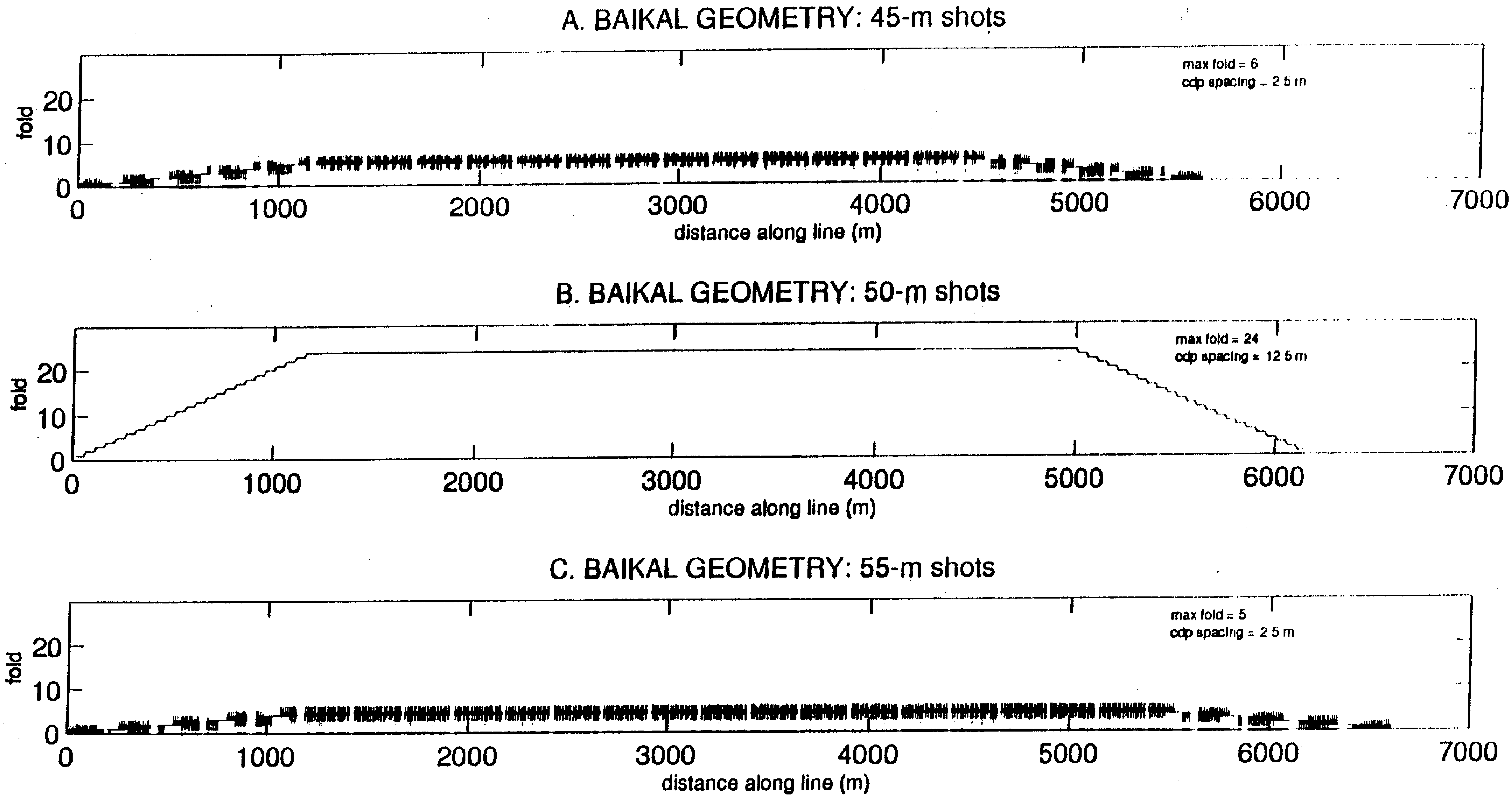

Figure 8. The effect of not maintaining a 50-m shot interval on the multichannel seismic processing geometry. The expected fold coverage for the receiver geometry used in the 1992 Lake Baikal cruise is indicated for 45-m shots (upper), 50-m shots (middle) and 55-m shots (lower). Deviations from the 50-m ideal shot spacing cause spatial smearing of the data, as indicated by the lower fold coverage for the 45-m and 55-m cases, but these variations are not likely to significantly impact the velocity estimates because of the low frequencies used in the survey. Note how the deviations from actual 50-m spacing change estimates of line length, and these differences need to be accounted for in estimating distances during interpretation of the multichannel profiles.

the seismic signal, i.e., the fresnel zone, at these frequencies is on the order of tens of meters. Shot intervals up to 7 m different than the ideal interval (i.e., 57-m shot intervals) would be inconsequential in velocity calculations.

A consequence of the navigational uncertainties is that some horizontal smearing of the data will occur, particlulary for lines where the mean firing rate differs from 50 m by more than 5 m. Figure 8 shows the fold coverage calculated using the Baikal multichannel source-receiver configuration (Agena et al., 1994) for 100 shots at 3 firing intervals: 45 m (top), 50 m (middle), and 55 m (bottom). In the ideal case (50 m), the fold coverage increases from 0 to 24 over common depth point (cdp) intervals of 12.5 m. For the 45-m case, the fold increases in a jerky pattern up to 6, and fluctuates between 4 and 6 for the bulk of the line with a cdp interval of 2.5 m. Similarly, the 55-m case only reaches maximum fold of 5 and fluctuates between 3 and 5, also with a cdp interval of 2.5 m. Merging 4 adjacent cdps from the 45-m and 55-m cases would produce 12.5-m binned cdps containing 24 traces, similar to the ideal 50-m case. The result is spatial smearing of the data horizontally. The low frequencies and size of the fresnel zone render most of this smearing inconsequential. However, the effect will be most pronounced in regions of steep relief, which are common in Lake Baikal along Academician Ridge and at the sides of the lake.

Another consequence of the navigational uncertainty is miscalculation of total line length and distances between cdps on the multichannel profiles. Figure 5 shows that the total line length for the line shot with 45-m intervals is 5645 m, whereas it is 6150 m and 6635 m for the 50-m and 55-m cases respectively. Distances measured off the seismic profiles should be corrected for the mean shot interval. Table 1 gives the best estimates of mean shot interval and line lengths for each line in Baikal.

The two missed shots associated with each tape change during the second half of the cruise require a small geometry correction in sorting and stacking the multichannel data. A comparison between a part of line 13 processed with and without the missed shots (Figure 9) shows that the character of the seismic data is essentially unchanged, but that certain details of the profile, for example, offset and overlap along a fault surface (arrow), differ. The fault trace that lines up with the arrow is sharper and more distinct on the profile with the corrections (Figure 9B). This emphasizes the importance of accurate navigation for processing of the multichannel data, particularly in structurally complex regions.

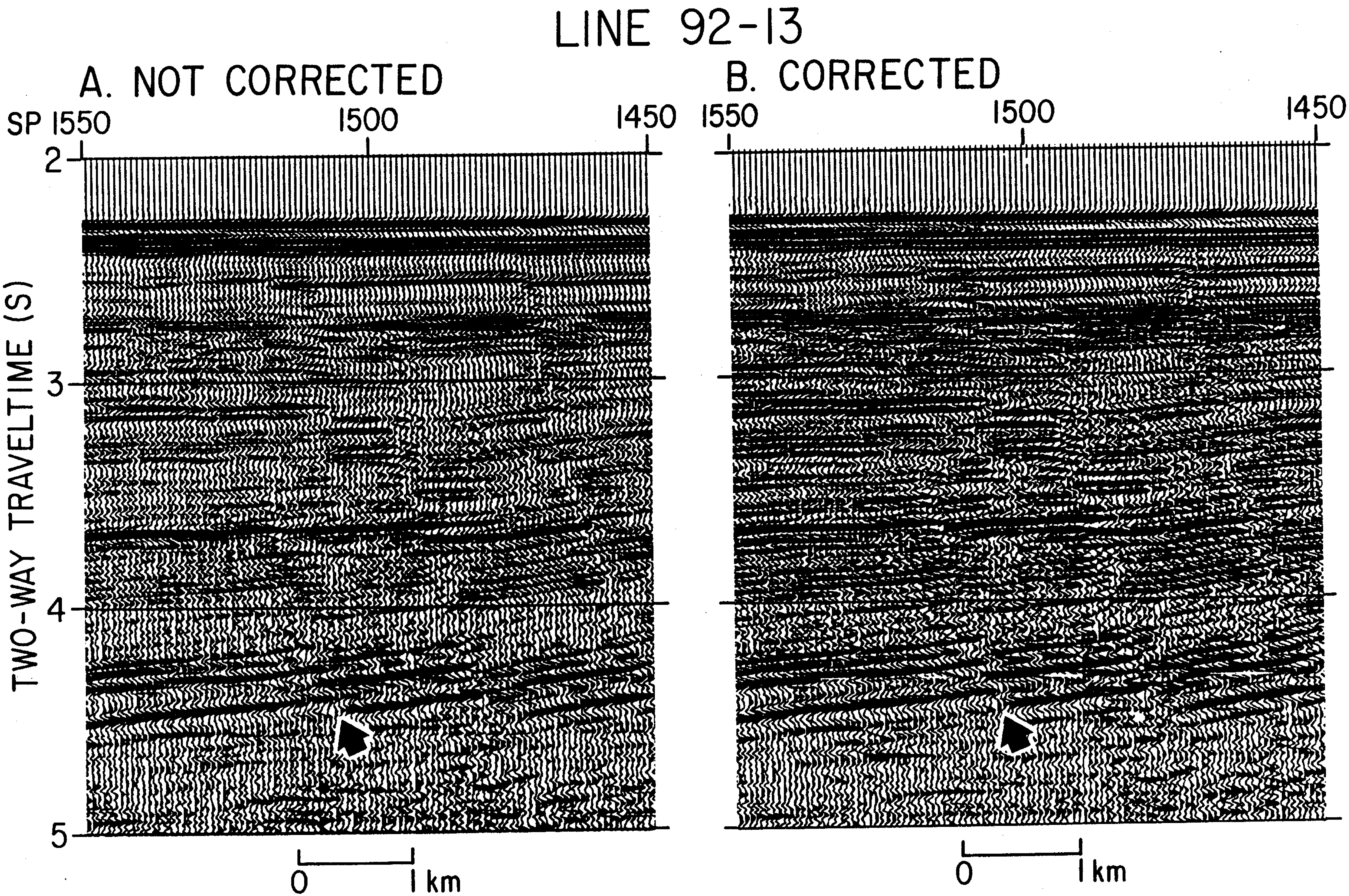

Figure 9: Comparison of migrated versions of a part of line 13 in the Central Basin with no corrections for missing shots (A) and proper geometry including missing shots (B). The profiles are nearly identical, but details of pinchout and overlap at a fault offset (arrow) differ slightly.

CONCLUSIONS

The navigation data collected on the 1992 Lake Baikal multichannel seismic reflection cruise posed a challenge to processing because of difficulties in assigning times to shot points. The salient conclusions that have resulted from this study are:

(1) Three sources contributed to uncertainty in navigation: inherent measurement limitations, poor logging of the shot-time calibration points, and missing shots. The measurement error varies from 6 - 22 m. The error associated with shot-time logging ranges from about 2 m (whole second logging) to 70 m (whole minute logging). Error associated with the missing shots is greatest at the position of the missed shots and decreases toward the shot-time calibration points.

(2) The scatter associated with the raw GPS data varies between lines and can be very noisy (>10 m per each 10-s interval) or very quiet (<2 m per each 10-s interval). Most of the scatter in the raw navigation is a function of variations in HDOP value and reflects uncertainty introduced by changing satellite geometries used to compute successive locations.

(3) After careful editing and processing of the raw navigation and calibration files, the quality of each line was assigned a rating of:

Excellent:	28 lines	6-12 m uncertainty
Good:	7 lines	12-24 m uncertainty
Poor:	13 lines	>50 m uncertainty

(4) The lines rated "Poor" generally occur in the southern Selenga Delta area. This is because the southern Selenga Delta was the first region profiled and includes the largest shot-time calibration errors.

(5) The assumption of a 50-m firing interval used to process the multichannel seismic data is valid and within the navigational uncertainty associated with shot locations. Actual deviations from 50 m are not likely to affect velocity estimates, but will cause some spatial smearing of the data, particularly in regions of steep relief. Distances measured off the seismic profiles should be corrected for actual shot distances of each line, rather than the assumed distance of 50 m.

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