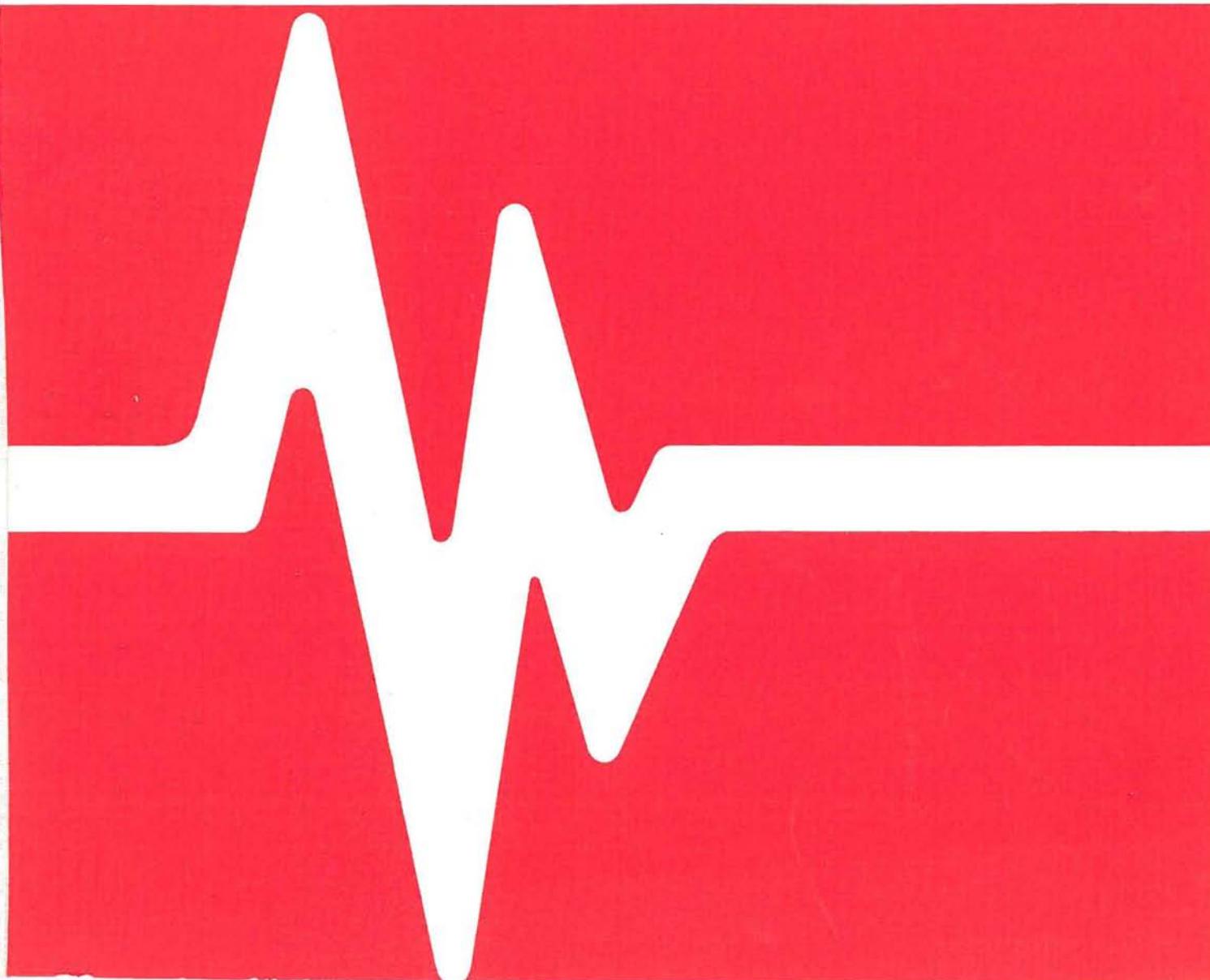


Underwater Noise Study from the Icebreaker "John A. MacDonald"

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Report 85.133

UNDERWATER NOISE STUDY
FROM THE ICEBREAKER
"JOHN A. MACDONALD"

by

Lars Thiele

December 1988



PREFACE

This report describes the results obtained from an underwater noise study performed during a voyage with the Canadian ice-breaker "JOHN A. MACDONALD" in Baffin Bay and Lancaster Sound in the summer (June - July) 1983.

The study was carried out as a part of the assessment of the impact on the marine environment caused by the "Arctic Pilot Project". This project included plans to ship liquified natural gas in large icebreaking carriers through Baffin Bay and Davis Strait.

The underwater noise study was initiated by the Department of Indian Affairs and Northern Development (DIAND) in collaboration with the Canadian Coast Guard who made the icebreaker available for the measurements.

The underwater noise measurements were performed by two teams of acousticians, one Canadian and one Danish team working parallel with each other. This report describes the results obtained by the Danish team. The results from the Canadian team are reported separately by Charles Greene, Ref. /3/.

The Danish part of the field measurements, the signal analysis and the reporting has been funded by Greenland Environment Research Institute.

The measurements were planned and performed by Ødegaard & Danne-skiold-Samsøe ApS. Bertel Møhl, from the University of Aarhus, participated in the field measurements.

Special thanks are expressed to the following who participated in the investigation and offered valuable help during the measurements: Ted Langtry (DIAND), Ian Marr (Canadian Coast Guard), Jim McComiskey (Gulf Canada Resources Inc.), Charles Greene and Greg Monroy (Greeneridge Sciences) and the officers and crew of the "JOHN A. MACDONALD".



SUMMARY

The underwater noise study performed from the Canadian icebreaker "John A. MacDonald" involved measurements of ambient noise, sound transmission loss and ship radiated noise.

The ambient noise was measured in Baffin Bay in a pack ice area (Location A) and in Lancaster Sound in a fast ice covered area (Location B) and at the ice edge between the fast ice cover and the open water (Location C). The results obtained at Locations A and C were dominated by sounds from marine mammals while there were no sounds of biological origin at Location B. At this location, the ambient noise level was very low and at high frequencies the levels measured at Location B were up to 20 dB lower than measured at Locations A and C. The magnitude of the measured ambient noise at Locations A and C is within the range of the noise levels found during other measurements in similar areas.

The sound transmission loss was measured at Locations A and B for five different distances in a range of 0.7 km up to 35 km. The transmission loss measurements were performed with small explosive charges used as sound sources. The results illustrate the variation in the transmission loss with frequency, distance, depth and location. The influence of the ice cover can be seen as an increase in the transmission loss at long distances. The measured transmission losses correspond reasonably well with the losses predicted by a FFP computer programme applying estimated input data from the area.

The noise radiated from "John A. MacDonald" could be detected for low frequencies at a distance of 55 km away from the measurement site at Location C. At a distance of 35 km the noise from the ship was exceeding the ambient noise level in the entire frequency range 20-5000 Hz at Location B.

The analysis of the recorded noise shows that the radiated noise from the icebreaker is dominated by cavitation noise generated by the propellers. The noise generated by the machinery or by the impact of the ship with the ice cover, does not contribute significantly to the noise level measured at some distance from the ship.

The maximum free field source strength of the radiated noise from the ship occurred when the propellers were operated with reversed revolutions. During the sailing ahead load conditions, the source strength was approximately 5-10 dB lower. The measured source strengths agree well with the suggested prediction model for expected cavitation noise.

In general, the presented measured source strengths from the ice-covered area in the present study are somewhat lower than the source strength measured in another study performed with the same ship sailing in open water on a naval sound range. This again indicates that the icebreaking itself does not contribute to the overall radiated noise.



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1. INTRODUCTION

One of the main problems with the exploration of energy resources in the Canadian Arctic is the transportation of oil or gas to the markets in the south. One project, the "Arctic Pilot Project, (APP)", involved transportation of liquified natural gas (LNG) in large icebreaking tankers. The tankers' route was planned to be from Melville Island through Lancaster Sound, Baffin Bay and Davis Strait to a harbour in the South of Canada or in Europe, see Figure 1.

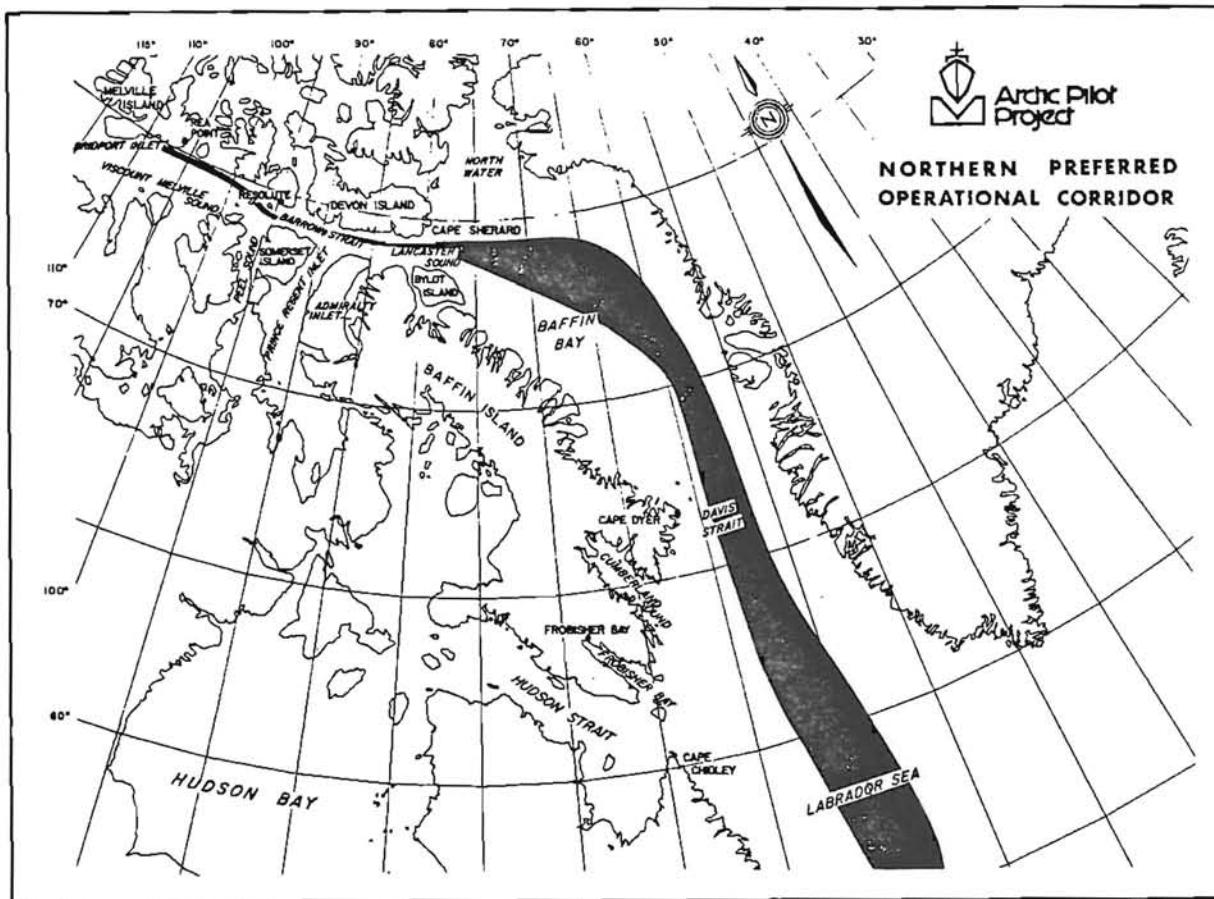


Figure 1.
Route of the LNG-carriers planned by the "Arctic Pilot Project".

The traffic should be performed on a year round basis and the ships were therefore designed with very powerful machinery due to the heavy ice conditions occurring during winter.



Concern was raised that the underwater noise radiated from the LNG-carriers would influence the acoustic environment in the sea, on which especially the marine mammals are dependent. Presently, traffic in the area is only performed by few and small ships and only during the ice-free summer period.

In order to evaluate the impact of ship generated noise on the marine environment, it is necessary to know the following parameters:

- The route to be taken and the condition under which the ships will be sailing.
- The source strength of the radiated noise from the ships under the actual load conditions.
- The sound transmission properties in the sea along the route.
- The ambient noise caused by natural sources, e.g. by ice.

Many studies which have been initiated partly by the "Arctic Pilot Project" and partly by Canadian and Danish authorities have dealt with these parameters. The "Arctic Pilot Project" has published their main results in a comprehensive report called "Integrated Route Analysis". Ref. /1/. This report describes the planned route, sailing conditions, ice distribution, expected radiated noise, ambient noise etc. Several other investigations, without connections to the APP, have been performed in Arctic waters in order to estimate the noise exposure from shipping and the associated behavior of the marine mammals present in these areas.

The planned route for the LNG-tankers would involve passing close by the west coast of Greenland. The authorities in Greenland and in Denmark have therefore also been involved in the evaluation of the impact. In 1980, the "Arctic Pilot Project Working Group" was



formed with participants from Canada, U.S.A., Greenland and Denmark. In this connection studies of the noise aspects have been performed by Ødegaard & Danneskiold-Samsøe ApS, Ref. /4/, /5/, /6/, /7/ and /8/ as consultants for Greenland Environment Research Institute.

The contributions to a workshop held in Toronto 1981 at which especially the noise problems were discussed are described in Ref. /9/.

The present report describes the results of measurements carried out from a Canadian icebreaker in order to obtain more data which can be used for the evaluation of the impact of shipping in Arctic waters. The voyage with "JOHN A. MACDONALD" was an excellent opportunity to investigate all the above-mentioned parameters under realistic conditions.

The main purpose of the measurements were:

- to determine the source strength of the radiated noise under different sailing conditions,
- to investigate the noise generated by the breaking of the ice,
- to measure the sound transmission loss in ice-covered areas,
- to measure the noise from the icebreaker at large distances,
- to measure the ambient underwater noise level, and
- to compare the measured data with results of prediction models or results obtained at previous investigations.



2. MEASUREMENT PROGRAMME

The underwater noise study was performed during a voyage with the Canadian icebreaker CCGS "JOHN A. MACDONALD" in June 1983. The icebreaker was assisting the ore carrier M/V "ARCTIC" on its trip to the Nanisivik mine in Admiralty Inlet.

The main data for the "JOHN A. MACDONALD" are as follows:

Length	: 96 metres
Dead-weight	: 3685 tonnes
Propulsion	: Diesel Electric with 9 diesel generators and 3 electric propulsion motors.
Total power	: 11200 kW ~15000 SHP
Propellers	: One centre, two wing. Diameter 4.1 m, 4 blades, fixed pitch.
Revolutions of propellers: Max. 150 rpm	

More detailed information about the icebreaker is given in Appendix A.

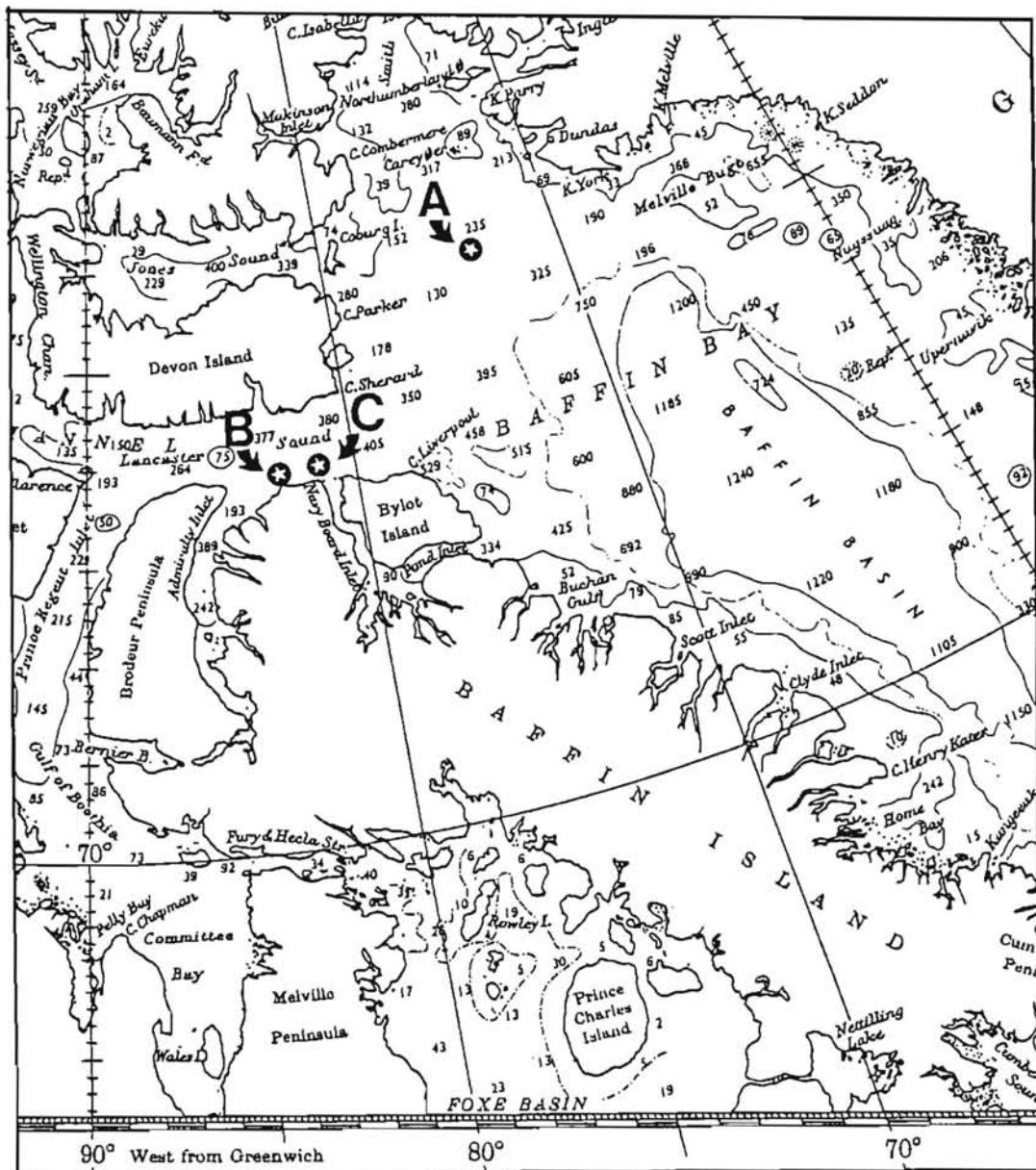
The route sailed by "JOHN A. MACDONALD" was from Halifax in Nova Scotia, along the west coast of Greenland, to Lancaster Sound and Admiralty Inlet. This route offered a very good opportunity to perform underwater noise measurements under various ice-conditions. Measurements were carried out at three different locations as shown in Figure 2.

Location A was in the northern Baffin Bay between Thule in North Greenland and Devon Island, Canada. The area was dominated by pack ice with some open water areas and some large floes. The ice thickness was less than 1 metre. The water depth was approximately 400 metres.



Location B was in the shore fast ice of Lancaster Sound north of Borden Peninsula. The ice thickness was approximately 2.5 metres with few ridges. The water depth was approximately 600 metres.

Location C was at the ice-edge where the fast ice in Lancaster Sound changed to open water. At the time of the measurements the ice-edge was located off Navy Board Inlet. The water depth was approximately 500 metres.





A more detailed description of the geographic locations, ice-conditions, hydrographic data etc. is given in Appendix B.

The sound study involved measurements of ambient noise, sound transmission loss and ship radiated noise. The measurement programme for these parameters are described in the following sections 2.1, 2.2 and 2.3.

2.1 Ambient Noise

The ambient underwater noise was measured at all three locations (A, B and C). As the measurements were carried out in the course of a short period of time, the results do not pretend to give a complete description of the ambient noise in the area. Nevertheless, the measurements were a good opportunity to obtain a reasonable indication of the ambient noise under various ice-conditions and the results can become valuable when compared with the data achieved previously in other studies.

The measurements were carried out with a high sensitivity piezoelectric hydrophone with build-in preamplifier, Brüel & Kjær type 8101. The signals from the hydrophone was recorded on a precision measuring tape recorder, Nagra type IS-D. The instrumentation set-up was calibrated with a hydrophone calibrator, Brüel & Kjær type 4223, and the calibration signal was recorded on the tape.

The hydrophone was placed at a depth of 50 metres below the surface for the measurements performed at locations A and B. At location C the hydrophone depth was 9 metres. An additional measurement was carried out in Lancaster Sound (location B) with hydrophone depths of 5, 50 and 100 metres applying a 4 channel tape recorder, Brüel & Kjær 7006.

All measurements of the ambient noise at location A and B were carried out with the ice-breaker situated 35 km away from the measurement site and with all main engines stopped. Furthermore, the M/V "ARCTIC" was stopped.



At location C the underwater noise was dominated by sounds from marine mammals such as beluga, narwhale, bowheadwhale and various seals. During the measurements "JOHN A. MACDONALD" was breaking ice at a distance of approximately 55 km and the noise generated by the ship was clearly detectable on the recording.

2.2 Sound Transmission Loss

Measurements of the sound transmission loss were performed in order to be able to calculate the source strength of the radiated underwater noise from the icebreaker and to evaluate the sound transmission properties in the various areas. The transmission loss was measured in Baffin Bay (Location A) and in Lancaster Sound (Location B).

The measurements were carried out by means of small explosive charges used as sound sources. The transmission loss was determined by the difference between the pressure level measured at a source hydrophone close to the explosive charge and a receiver hydrophone at varying distances. The source hydrophone was placed close to the icebreaker and the receiver hydrophone at the measurement site on the ice.

The source signal of the shot was measured with the source hydrophone placed at a distance of 2 metres from the explosive charge. Small blasting caps with a content of 1 gramme of TNT were used as sound sources. They were fired from the aft end of the icebreaker at a depth of 4 metres, corresponding to the approximate depth of the cavitation centre of the propellers.

The pulse generated by the explosion was received at the measurement site on the ice by a set of 3 receiver hydrophones at depths of 5, 50 and 100 metres. The measurement set-up is illustrated in Figure 3.

A more detailed description of the measuring procedure and the analysis applied for the transmission loss measurements are given in Appendix D.



The distance between the source and the receiver hydrophones was at location A approx. 35, 18, 8, 2 and 1 km, and at location B approx. 35, 14, 7, 2 and 1 km. The distance was determined by use of a microwave system, type "Mini-Ranger".

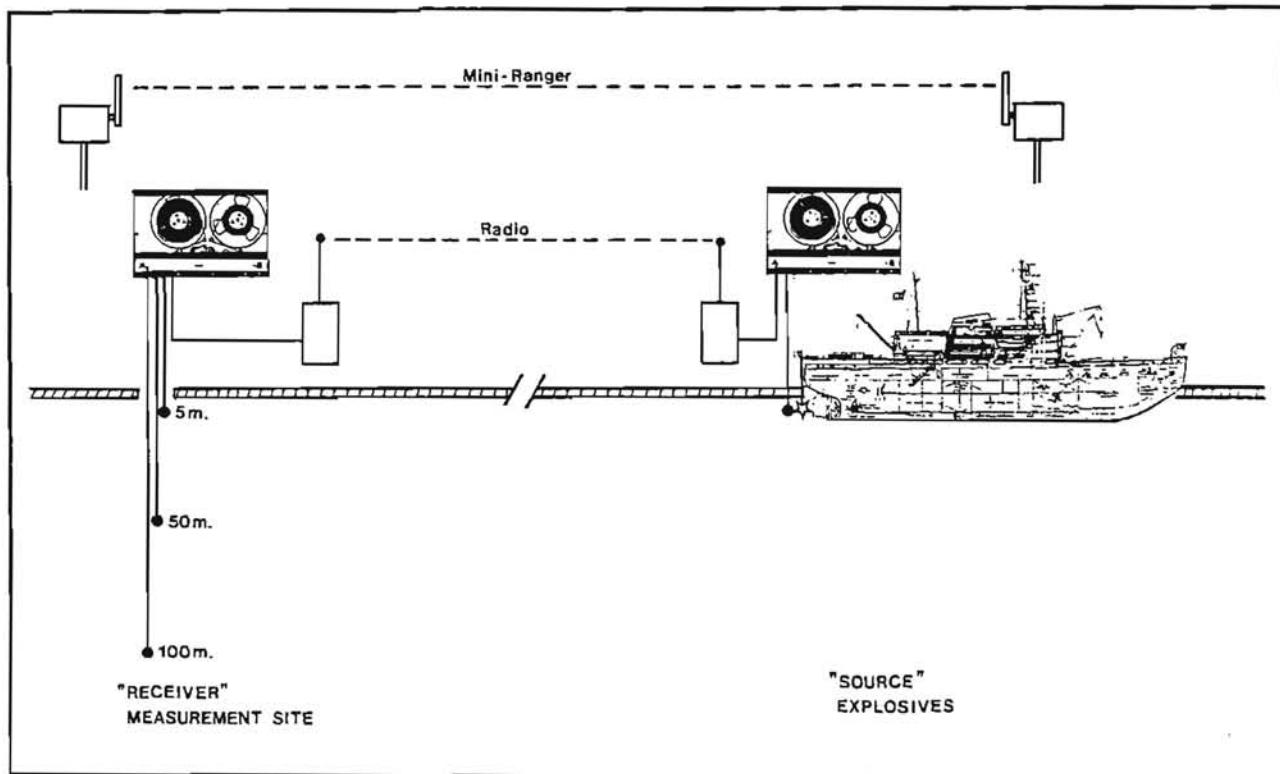


Figure 3.
Instrumentation set-up for transmission loss measurements.

Parallel to the shot experiments, transmission loss measurements were performed with an electro dynamic sound projector transmitting a set of pure tones. The results from this experiment are not included in this report but have been reported by Charles Greene, Ref. /3/.

2.3 Ship Radiated Noise

The main aim of the study was to achieve information about the level of the propeller noise at long distances from the ship and to calculate the equivalent source strength of the propeller noise with the icebreaker sailing under different load conditions including heavy icebreaking. Furthermore, it was the objec-



tive of the study to investigate whether the actual breaking of ice contributes significantly to the overall radiated underwater noise level.

In order to monitor the sailing conditions during the measurements, a recording was performed on board of the signals from two accelerometers and one tachometer. One accelerometer was placed in the bow of the ship in order to monitor the periods when the ship was breaking ice. The other accelerometer was placed on the shell plating in the aft end of the centre shaft tunnel close to all three propellers. The signal from this accelerometer was used as an indicator of the propeller load condition.

The tachometer was placed on the centre shaft and the signal was used to monitor the exact revolution rate of the centre propeller during the measurements. The signals from the accelerometers and the tachometer were recorded on a 4-channel tape recorder together with comments on time, position, engine load, ice conditions etc. applying a microphone on the bridge.

The underwater noise radiated from the ship was recorded from a measurement site placed on the ice, away from the icebreaker. At the measurement site, three hydrophones were immersed into the water through holes in the ice cover. The depths of the hydrophones were 5, 50 and 100 metres below the surface. The arrangement is shown in Figure 4.

The signals from the hydrophones were recorded by means of a 4-channel FM tape recorder, type Brüel & Kjær 7006. The fourth channel was used to record comments on time, weather conditions etc. together with the radio communication with the icebreaker. This radio communication was also recorded simultaneously on the tape recorder on board the icebreaker in order to match the two recordings.

During the measurements it was important to know the exact distance between the icebreaker and the measurement site. The distance was therefore determined with a very precise microwave



system, type Motorola "Mini Ranger". These distance readings, together with the distances and bearings taken from the radar, have been used to plot the positions given in Appendix B.

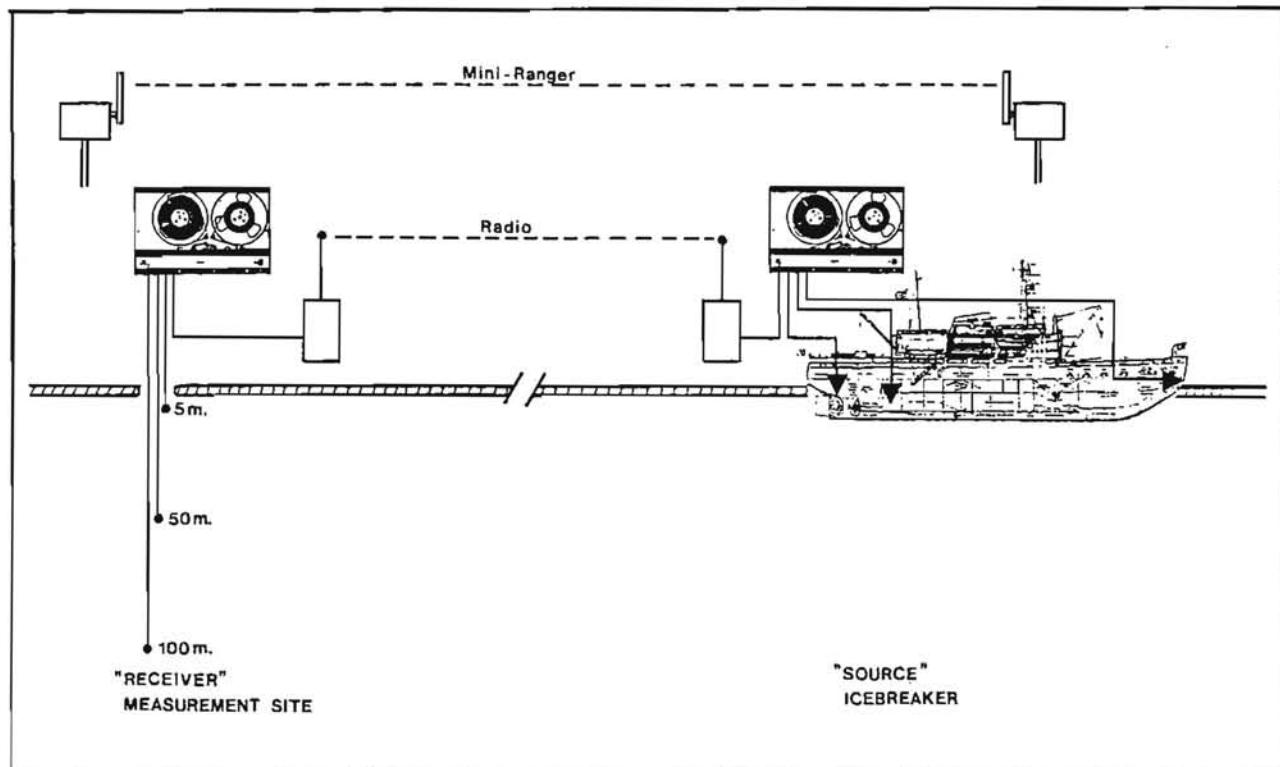


Figure 4.
Instrumentation set-up for the measurements of ship radiated noise.

At Location A in Baffin Bay, the measurements were performed from a stationary measurement site while the icebreaker approached and passed the site at a close distance. When the measurements started, the icebreaker was 35 kilometres away. Five stops were made in order to perform the transmission loss measurements. The sailing conditions varied during the test run corresponding to the change in ice conditions. Due to the light ice concentration, the icebreaker sailed mostly with low load and ramming was not necessary.

At Location B in Lancaster Sound the ice conditions were much heavier with 2.5 metres of fast ice. This meant that the ice-breaker had to perform constant ramming and it made only very slow progress. It was therefore necessary to move the measurement



site in order to obtain measurements at five different distances from the icebreaker. During the ramming procedure the load condition for the icebreaker changed periodically from full ahead, full astern and idle.

At Location C at the ice edge in Lancaster Sound additional measurements were performed, mostly with the aim of obtaining records of marine mammal vocalization. However, also the noise from the icebreaker could be heard on the recordings. As the icebreaker was 55 km away from this measurement site, the results also give valuable information about the ship noise at large distances.

3. RESULTS OF AMBIENT NOISE MEASUREMENTS

The ambient noise signal is non-stationary in character. In order to describe the ambient noise level, a statistical analysis of the recorded signals has been performed in the laboratory after the return from the measurements.

During the statistical analysis, the levels exceeded in 1, 50 and 90 percentage of the time, were found for the one-octave frequency bands with centre frequencies from 31.5 Hz to 4000 Hz. The integration time used was 250 ms.

Duration of the analysis for the recordings performed with the single channel Nagra IS-D tape recorder (recordings 1-7) was approximately 22 minutes. The additional measurements performed with the 4-channel Brüel & Kjær 7006 tape recorder (recordings 2A and 2B) had a duration of approximately 30 minutes.

Again it must be emphasized that the results given here do not pretend to give a total description of the ambient noise in the area. To do this, a much more detailed measurement programme has to be carried out. Also the recordings made at Locations A and C were totally dominated by biological sounds and at Location C influenced by noise generated by the icebreaker itself. Neverthe-



less the results can be used together with other results to form a basis for the evaluation of the natural acoustic environment in arctic waters.

3.1 Results from Baffin Bay and Lancaster Sound

The results of the statistical analysis for each of the recordings are given in Appendix C in which the spectrum levels L_1 , L_{50} and L_{99} are shown (levels exceeded in 1, 50 and 99 percentage of the time). Furthermore, a recording of the overall level versus time is shown and comments to the recordings are given. The statistical data are presented as spectrum levels expressed in dB re. $1 \mu\text{Pa}/\sqrt{\text{Hz}}$. The overall levels are recorded in the frequency interval 20-8000 Hz with an integration time of 250 ms.

An example of the statistical analysis is given in Figure 5 where the L_1 , L_{50} and L_{99} levels measured at Location B at a depth of 50 metres (recording No. 2) are shown. The corresponding record-

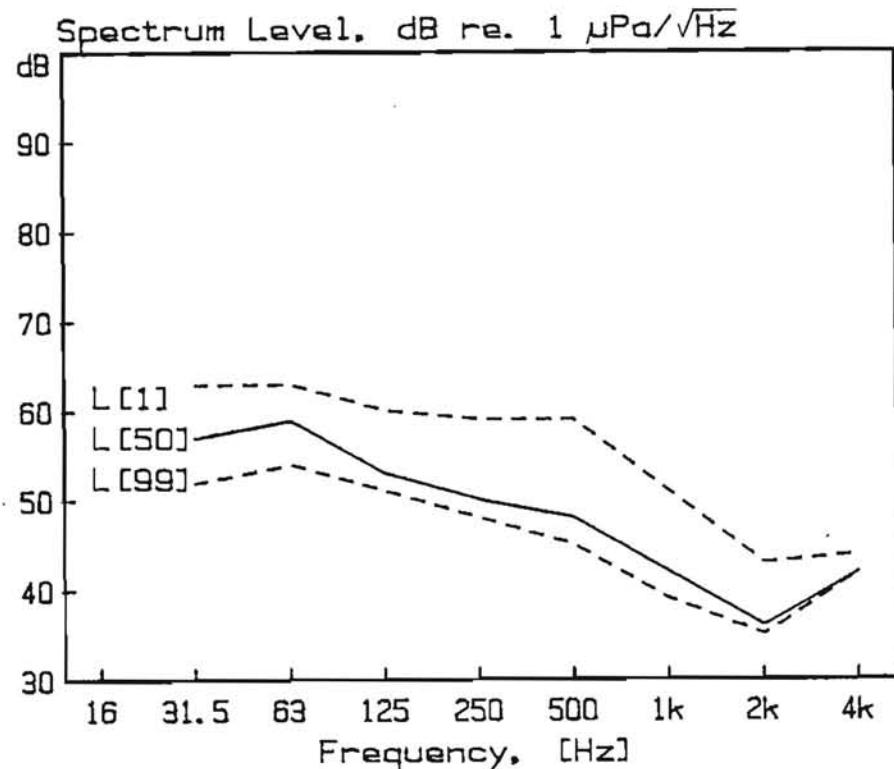


Figure 5:
Example of ambient noise measured in Lancaster Sound at Location B. Hydrophone depth 50 metres.



ing of the variation in the overall level for the same period of time is illustrated in Figure 6.

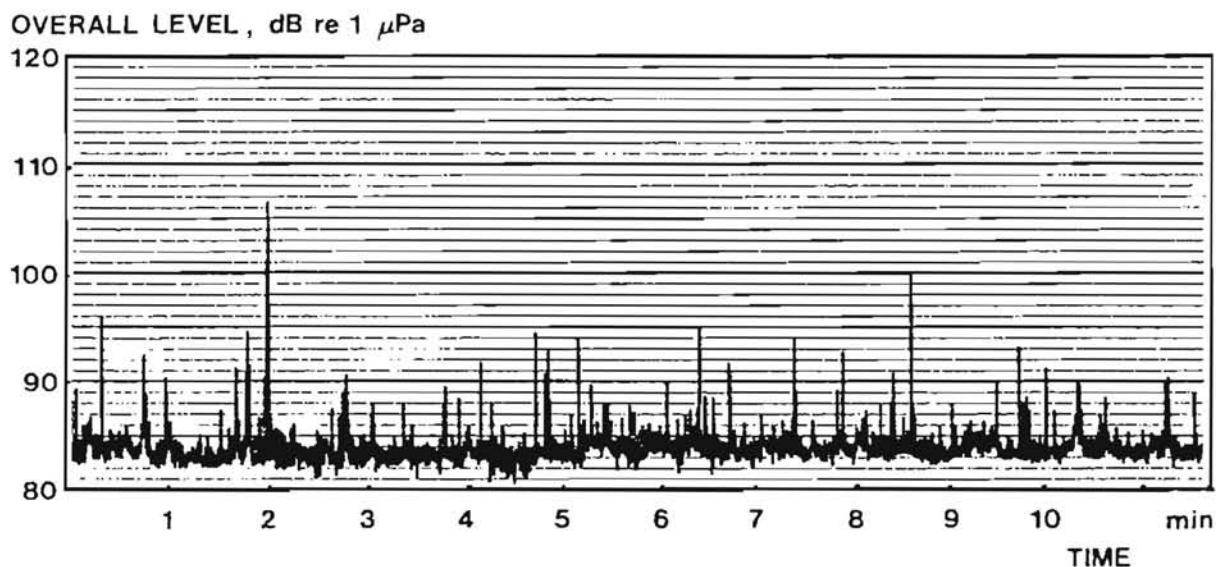


Figure 6.

Variation of the overall level in the frequency bandwidth 20-8000 Hz. Measured in Lancaster Sound at Location B. Hydrophone depth 50 metres.

As can be seen from the results given in Figures 5 and 6 as well as in Appendix C, the measured ambient noise levels are dependent on the time, the measurement position and the hydrophone depth. The variation in time, during a period of 10 minutes, is illustrated in Figure 6 which shows the typical character of arctic ambient noise with a relatively constant base level and strong noise pulses generated by the ice.

The variation in the measured L_{50} spectrum levels for the three locations are illustrated in Figure 7. It must be noted that the hydrophone depth was 50 metres at Locations A and B but 9 metres at Location C.

The influence of the hydrophone depth on the ambient noise level is illustrated in Figure 8. This figure shows the measured L_{50} spectrum levels from the Lancaster Sound fast ice (Location B) with hydrophone depths of 5 and 50 metres.

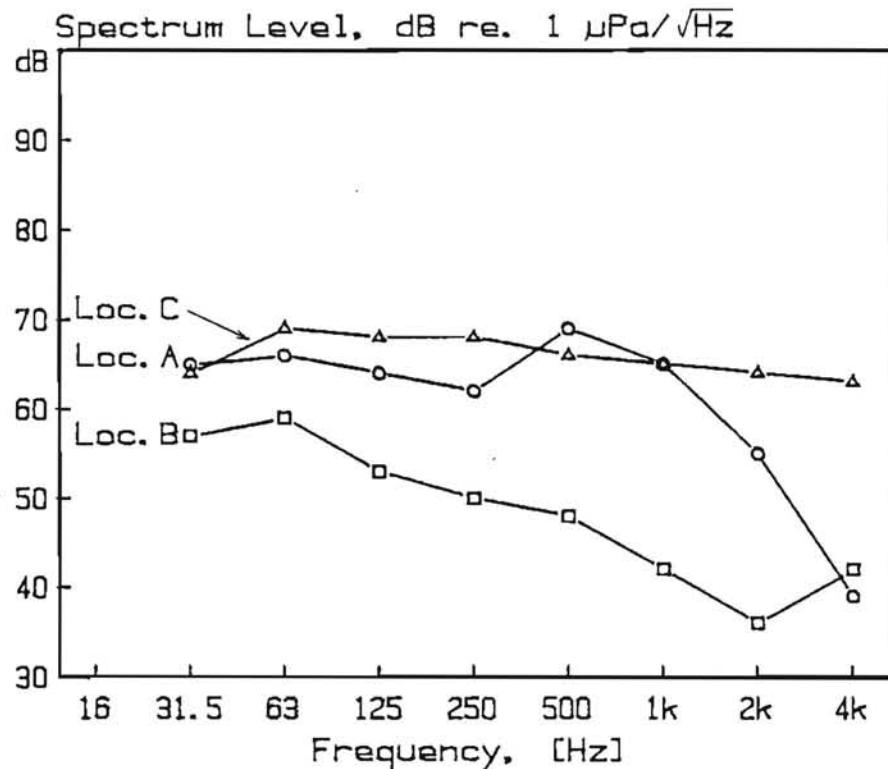


Figure 7.

The L_{50} spectrum levels measured in Baffin Bay (Location A), Lancaster Sound, fast ice (Location B), and from the ice edge (Location C).

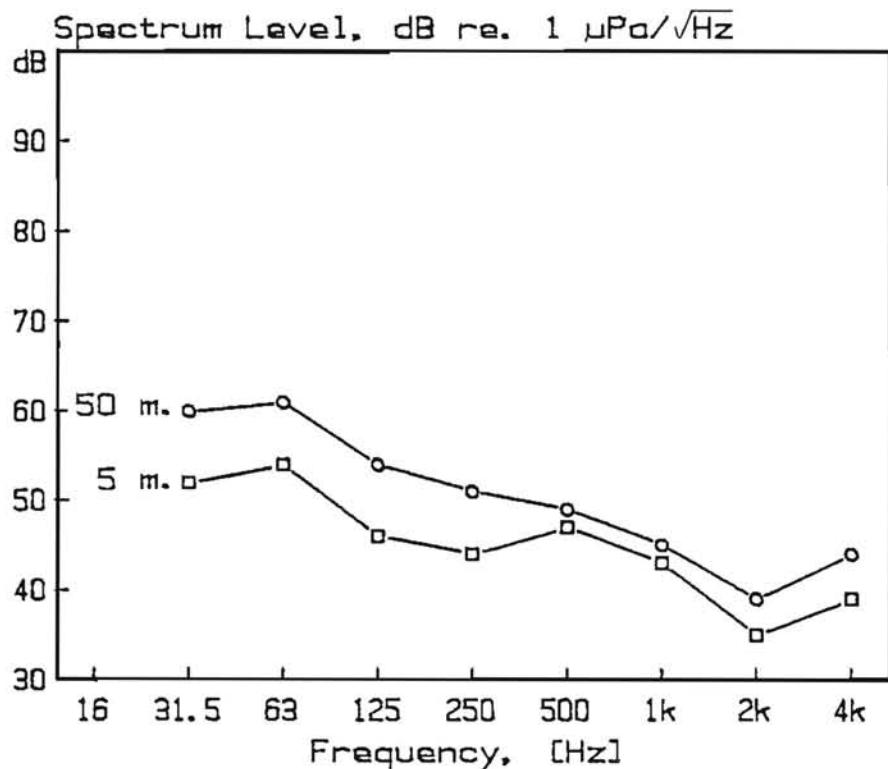


Figure 8.

The L_{50} spectrum levels measured in Lancaster Sound at Location B. Hydrophone depth 5 and 50 metres below the surface.



3.2 Measured Data Compared with Data from Other Studies

In order to evaluate the magnitude of the ambient noise measured during the present investigation, the results can be compared with other results obtained in arctic waters. In Figures 9 and 10, the measured levels are compared with results from investigations carried out in Northern Baffin Bay off Cape York and Thule where similar ice conditions occur, Thiele Ref. /7/ and /8/.

In Figure 9, the ambient noise measured at Location B (fast ice in Lancaster Sound) is compared with the results obtained off Cape York below a fast ice cover, Ref. /7/.

In Figure 10 the ambient noise measured at Locations A and C (pack ice and ice edge) is compared with results obtained off Thule during the summer in an area with open water and some pack ice, Ref. /8/.

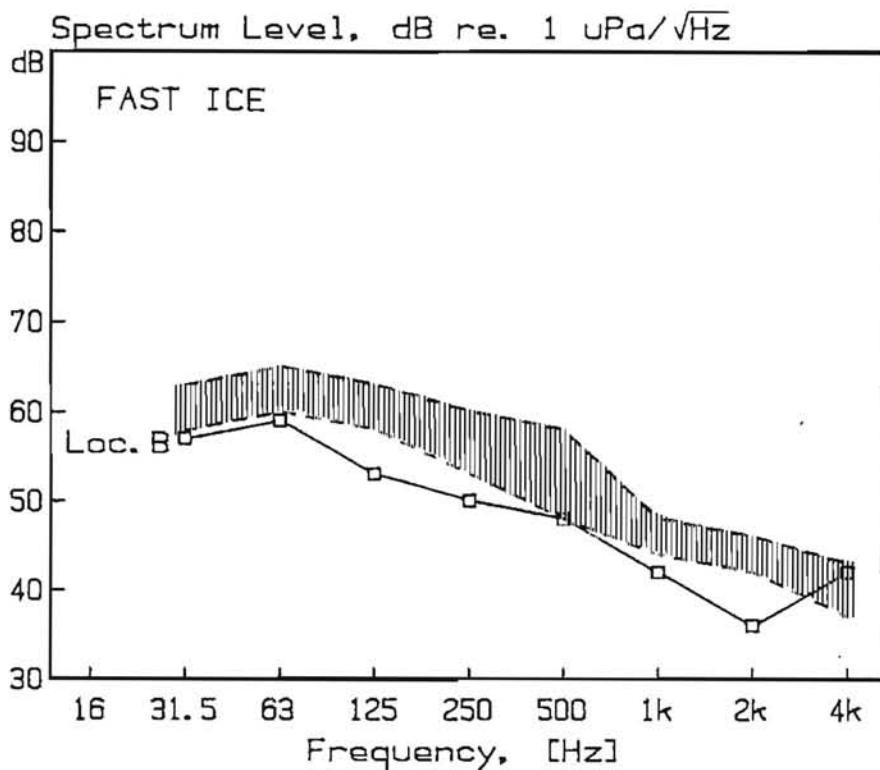


Figure 9.
Levels measured with fast ice (Location B) compared with the results of measurements off Cape York, also from an area with fast ice, Ref. /7/.

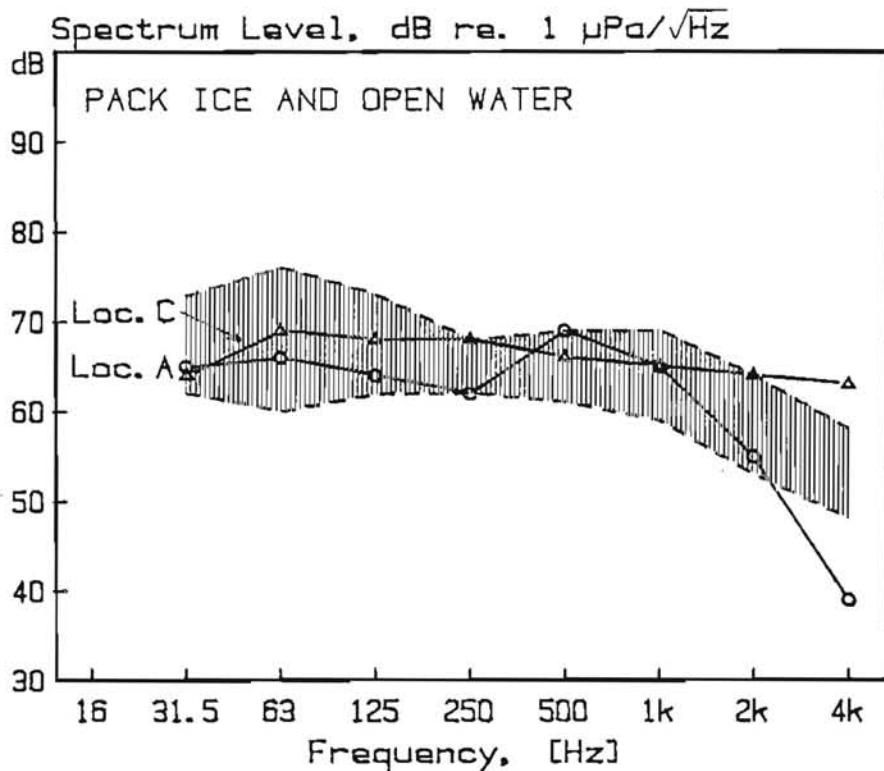


Figure 10.

Levels measured in the pack ice (Loc. A) and at the ice edge (Loc. C) compared with the results from measurements off Thule during the summer. Ref. /8/.

3.3 Discussion

The ambient underwater noise measurements have been carried out as part of this noise study in order to obtain additional data which can be used as a supplement to existing ambient noise studies.

The results of the measurements performed in Baffin Bay at Location A showed that the ambient noise was strongly influenced by biological sounds. The whistling sounds produced by the bearded seals were dominating at frequencies above 250 Hz. The pronounced peak at 500 Hz in the spectrum shown in Figure 7 for Location A can be ascribed to these sounds made by the bearded seals. Even inclusive of the contribution from the bearded seals, the magni-



tude of the ambient noise recorded in Baffin Bay is within the range of the noise levels recorded off Thule, Ref. /8/, at the same time of the year.

The recordings performed in Lancaster Sound at Location B in the fast ice area indicate very low levels of ambient noise. These recordings were not affected by marine mammal sounds and the noise generated by natural sources was so low that it was close to the detection limit of the highly sensitive precision hydrophone used for the measurements. The magnitude of the recorded ambient noise is lower than found during the other study performed below a fast ice cover off Cape York, Ref. /7/.

The additional measurements carried out at Location B at two different depths (5 and 50 metres) show the effect of the surface. It is observed that the highest noise levels are recorded with the deep hydrophone while the level at the shallow hydrophone is approximately 5-10 dB lower. At the shallow hydrophone the transmitted sound waves will be attenuated due to interaction between the sound waves and their surface reflected parts. The measured difference indicates that the ambient noise is not generated by the ice cover locally but by many distant sources which are summarized. If the main part of the noise was generated in the ice cover close to the measurement site then the highest noise level would have occurred for the shallow hydrophone which is closest to the ice-cover.

At the ice edge in Lancaster Sound, Location C, the recorded ambient noise was totally dominated by the sounds produced by marine mammals. Also the noise generated by the distant ice-breaker contributed to the recorded levels at low frequencies. Even with these contributions included, the magnitude of the recorded noise did not exceed the range of noise found off Thule, Ref. /8/.



4. RESULTS OF SOUND TRANSMISSION LOSS MEASUREMENTS

As described in section 3.2 and Appendix D, the sound transmission loss measurements were carried out by means of small explosive charges used as sound sources and by determination of the sound pressure level close to the source and at a receiver location placed at varying distances.

The surface reflections of the pressure pulses generated by the shot affect the shape of the frequency spectrum measured at the source hydrophone and results in an apparent dipole directivity for the source strength. Due to this effect, the frequency spectrum of the source signal will be dependent on the depth of the explosive charge when fired. To eliminate the effect of these reflections on the frequency spectrum they have been removed by editing the digitized time function by means of a computer. By Fourier transforming the edited time function, it is possible to obtain an estimated free field frequency spectrum. The result corresponds to the spectrum of a monopole source placed in an infinite body of water.

The transmission loss is found as the difference between the free field source spectrum referring to a distance of one metre and the spectrum actually measured at the receiver. The results are given in the two frequency ranges 0-500 Hz and 0-5000 Hz. The detailed procedure used for the analysis is described in Appendix D.

When the source strength of the noise generated by the ship is calculated by applying the sound transmission loss found as described above, it will be independent of the source depth. Thereby the monopole source strength for this ship can be compared with the monopole source strength of other ships independent of propeller depth and draught.



4.1 Results from Baffin Bay and Lancaster Sound

The detailed results from all the shot experiments are given in Appendix D. An example of the measured transmission loss for a single shot is given in Figure 11. This figure shows the result from Baffin Bay (Location A) with a distance of 1700 metres between the icebreaker and the receiver hydrophones placed at depths of 5, 50 and 100 metres.

The transmission loss per 1/3-octave frequency bands has been determined from the curves given in Appendix D as an average of the number of shots fired at each distance. The average levels have been calculated, on an energy basis, in each 1/3-octave frequency band with centre frequencies from 25 Hz to 5000 Hz. Three shots were fired at each distance but as the gain setting had to be adjusted at every new distance, some of the shots were not applicable due to overload or low signal/noise ratio.

The main results in 1/3-octave frequency bands are given in Tables 1 and 2 and the variations are illustrated in Figures 12, 13, and 14.

In Tables 1 and 2 the transmission loss data in 1/3-octave frequency bands are given for each of the two locations at the three depths and five distances for the centre frequencies 25 Hz to 5000 Hz.

The curves in figure 12 illustrate the variation of the transmission loss versus frequency from the measurement in Baffin Bay and Lancaster Sound for five different distances with the receiver hydrophone depths of 5, 50 and 100 metres.

Figure 13 illustrates the variation of the transmission loss with distance for the measurements performed in Baffin Bay with a receiver hydrophone depth of 50 metres. Figure 14 shows similar curves from Lancaster Sound.

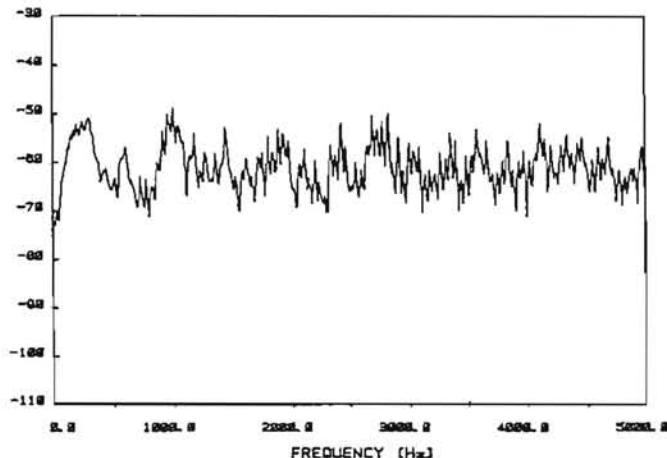
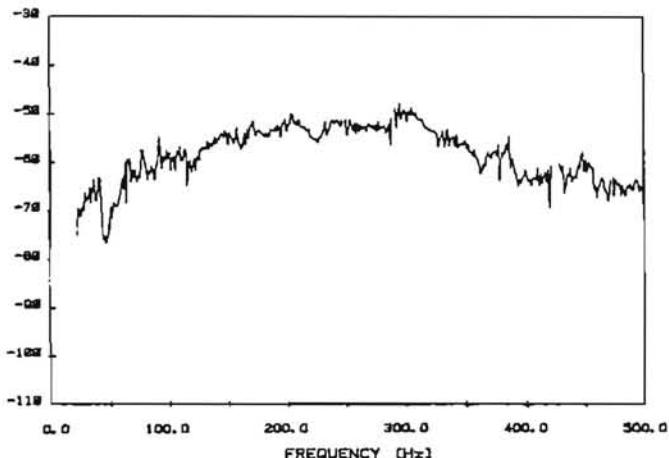
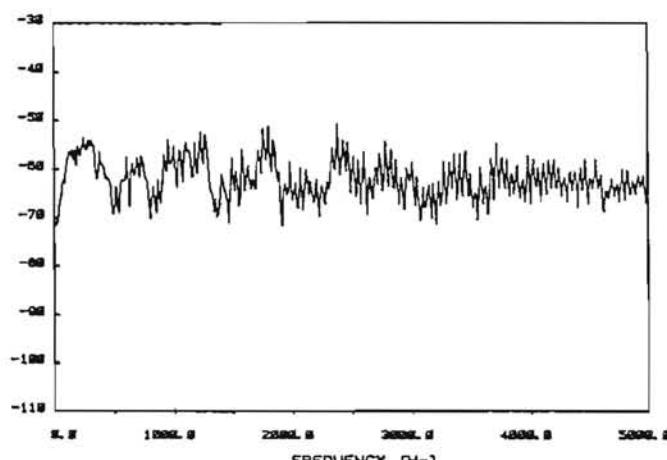
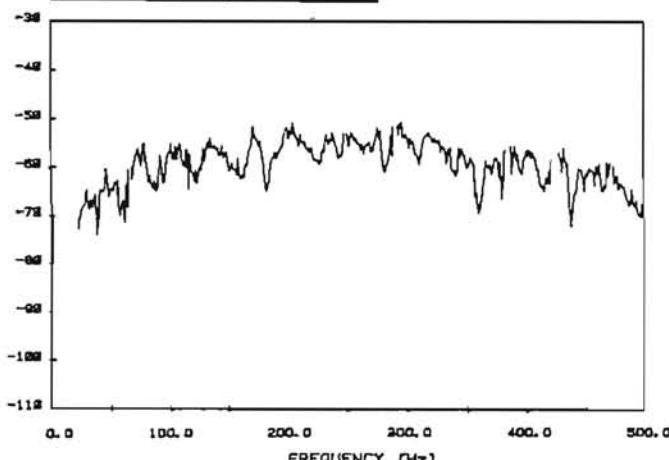
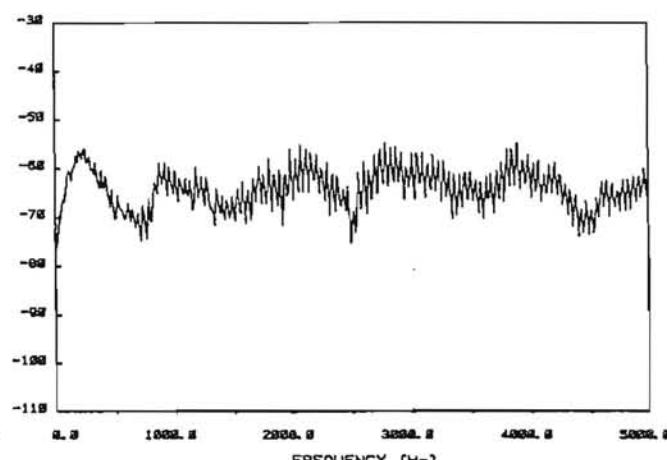
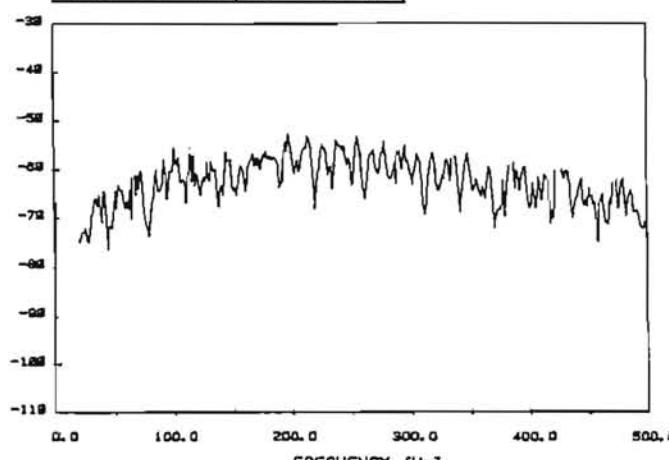
Receiver Depth 5 m :Receiver Depth 50 m :Receiver Depth 100 m :

Figure 11.

Measured transmission loss in Baffin Bay at Location A. Distance between source and receiver 1700 metres. Frequency range of curves in the left side: 0-500 Hz, right side: 0-5000 Hz.



Distance	675 m			1700 m			7770 m			17800 m			35000 m		
Hydrophone depth, m	5	50	100	5	50	100	5	50	100	5	50	100	5	50	100
Hz	dB	dB	dB	dB	dB	dB	dB	dB	dB	dB	dB	dB	dB	dB	dB
25	52	52	49	69	68	72	78	73	74	85	78	77	78	74	74
31.5	51	53	50	67	67	68	75	72	73	82	81	78	82	78	76
40	58	54	52	66	66	67	75	74	75	81	77	77	84	80	78
50	68	59	58	70	64	68	86	78	76	88	84	81	96	85	82
63	57	54	56	64	66	66	84	77	79	86	75	80	93	82	81
80	54	52	52	62	59	64	77	70	74	81	74	75	92	82	79
100	52	55	52	59	58	60	76	79	76	82	78	78	88	82	82
125	49	54	49	58	58	61	75	75	72	78	76	77	82	78	74
160	54	54	50	54	57	59	69	71	71	74	73	73	82	78	77
200	58	55	49	53	54	56	67	70	67	72	75	74	83	78	79
250	66	57	52	53	54	56	65	69	70	70	72	73	81	77	79
315	65	58	55	51	53	59	64	68	66	69	71	70	79	76	79
400	65	59	53	59	57	62	65	68	67	70	71	72	78	77	74
500	67	55	50	63	62	67	70	70	69	72	74	74	79	78	75
630	56	53	51	61	61	69	72	74	73	78	75	78	78	80	79
800	66	55	52	66	60	67	73	75	74	77	78	80	80	82	80
1000	64	56	53	54	58	62	69	70	70	77	77	80	82	78	80
1250	63	55	56	59	57	63	70	70	70	77	79	82	83	77	81
1600	63	55	55	62	59	64	75	75	75	75	78	78	83	85	84
2000	60	53	58	58	62	60	71	72	74	77	78	79	86	78	82
2500	60	54	56	58	58	65	76	76	76	77	81	81	88	82	86
3150	59	57	58	59	63	60	76	76	73	79	77	80	92	88	92
4000	58	58	59	58	60	60	74	77	72	80	80	85	96	89	93
5000	56	56	58	60	62	62	75	74	70	82	82	84	98	95	95

Table 1.
Transmission loss per 1/3-octave frequency bands measured in Baffin Bay at Location A.



Distance	1170 m			1880 m			6860 m			14470 m			35200 m		
Hydrophone depth, m	5	50	100	5	50	100	5	50	100	5	50	100	5	50	100
Hz	dB	dB	dB	dB	dB	dB	dB	dB	dB	dB	dB	dB	dB	dB	dB
25	61	59	59	73	70	65	78	75	68	74	70	62	97	89	81
31.5	59	58	58	72	71	68	76	78	72	74	71	67	98	89	84
40	60	62	58	73	72	71	76	79	69	75	74	68	99	91	88
50	64	63	63	77	76	75	84	80	81	79	79	75	105	95	93
63	59	60	58	65	67	66	78	76	73	73	72	68	97	91	92
80	58	58	58	70	72	74	81	78	78	82	78	77	105	95	93
100	60	59	61	70	71	74	81	75	79	80	78	77	105	98	94
125	53	57	55	66	67	68	80	79	76	85	83	82	103	97	92
160	52	54	51	68	67	67	76	75	75	78	82	75	100	93	88
200	58	56	54	68	67	68	74	73	76	80	81	80	99	92	92
250	58	58	58	71	65	68	70	71	75	78	80	80	96	91	90
315	57	57	53	70	66	67	68	72	72	75	77	78	92	87	90
400	59	55	57	68	67	67	65	68	71	76	76	77	85	86	89
500	60	54	58	71	67	67	62	67	66	74	75	78	87	87	90
630	60	58	63	68	62	60	60	66	67	72	74	77	83	84	88
800	65	58	63	71	64	63	61	66	67	73	73	76	84	84	88
1000	59	58	58	67	65	64	66	65	69	73	75	76	85	86	89
1250	67	62	61	66	64	65	63	69	69	69	76	77	88	89	90
1600	65	57	60	69	64	61	70	63	70	69	74	73	90	93	93
2000	66	60	59	69	64	60	67	69	72	69	74	76	93	94	97
2500	59	62	60	71	64	62	67	70	70	73	77	80	98	99	97
3150	62	59	60	68	62	58	69	71	67	79	81	80	98	100	96
4000	62	60	60	67	66	64	75	72	69	76	82	81	99	100	94
5000	60	60	59	67	64	63	68	68	70	79	78	78	99	102	91

Table 2.
Transmission loss per 1/3-octave frequency bands measured in Lancaster Sound at Location B.

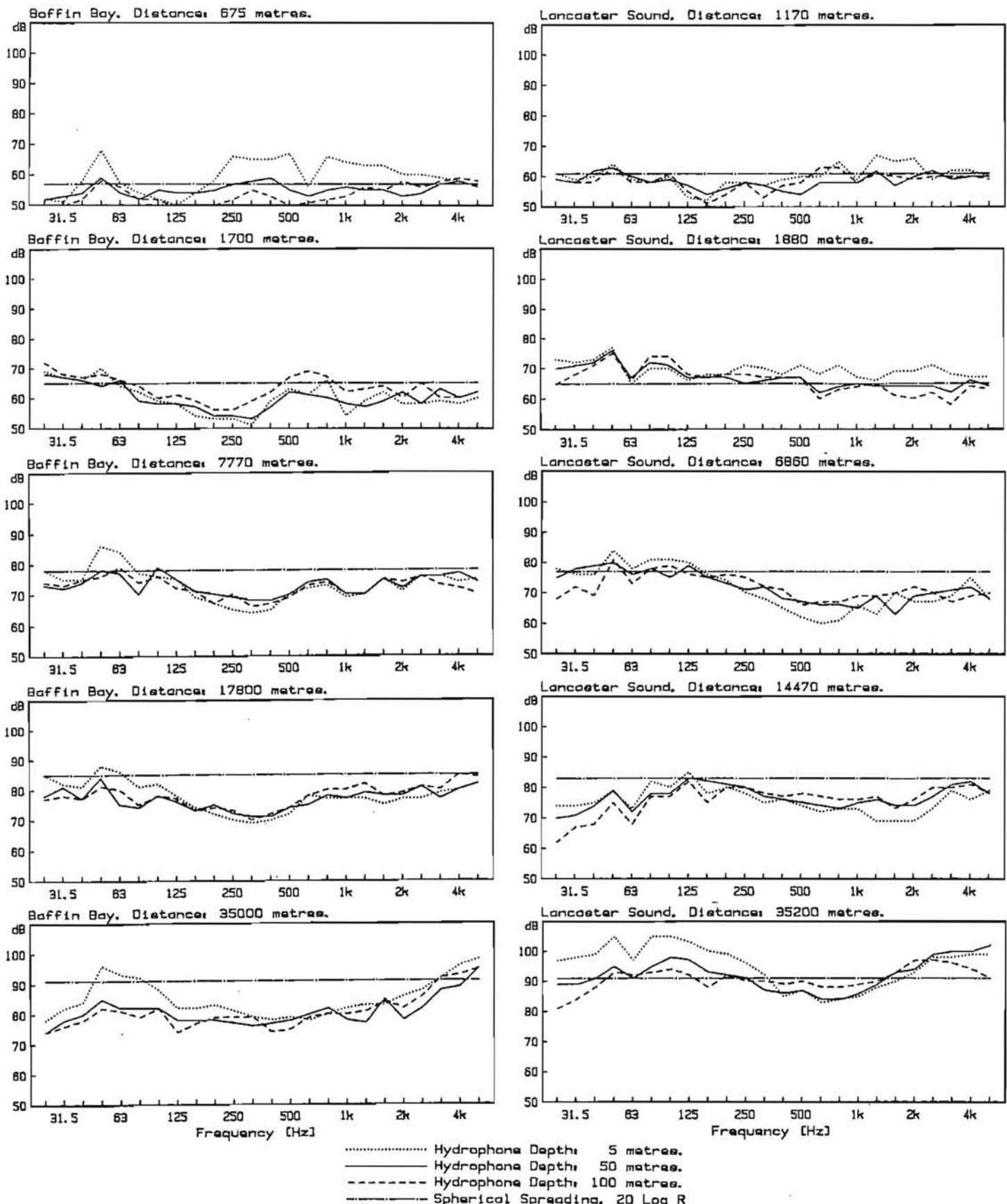


Figure 12.

Measured average transmission loss per 1/3-octave frequency bands measured in Baffin Bay at Location A (left side) and in Lancaster Sound at Location B (right side).

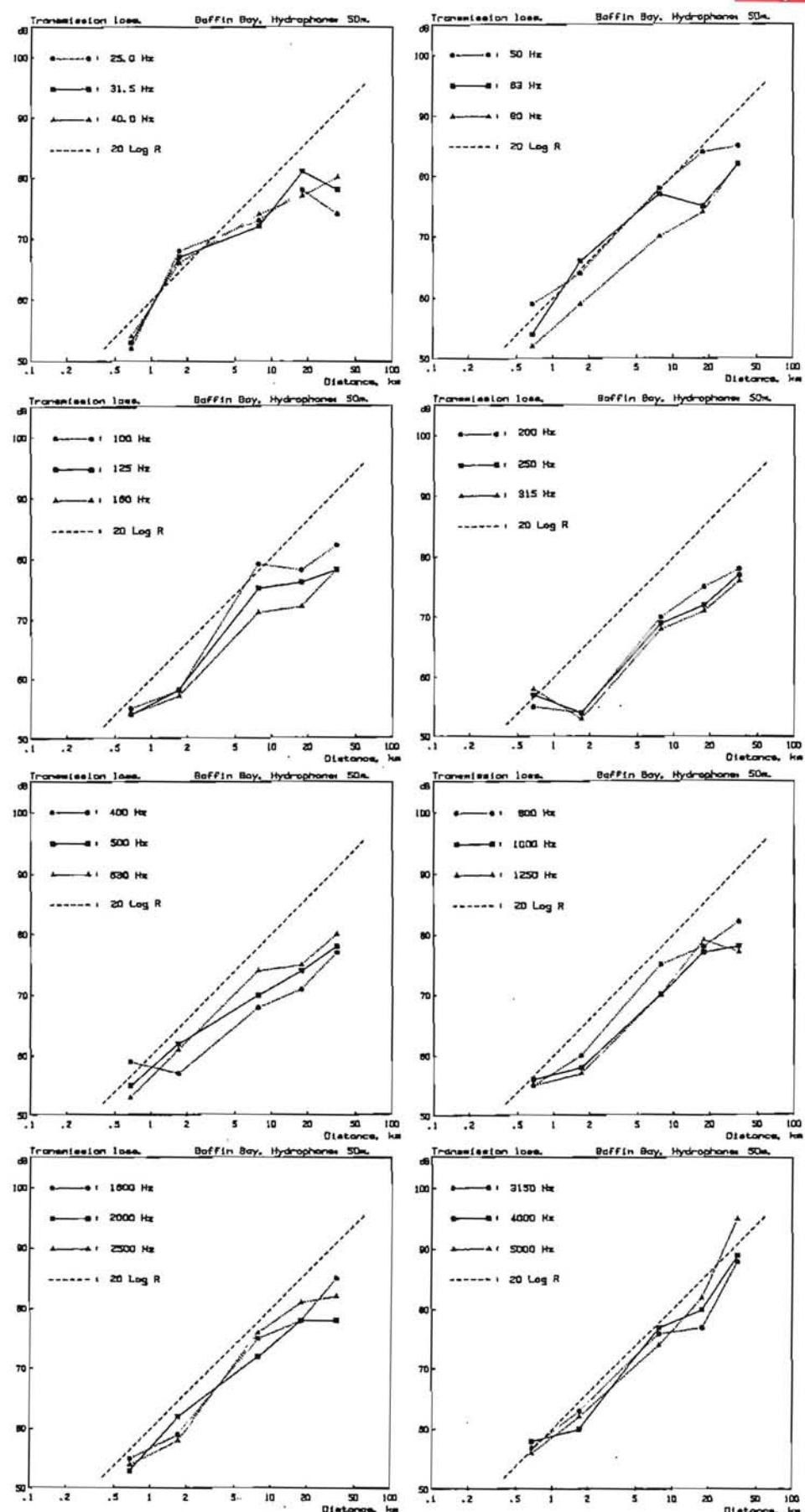


Figure 13.
Average sound transmission loss per 1/3-octave frequency bands versus distance. Baffin Bay at Location A. Hydrophone depth 50 metres.

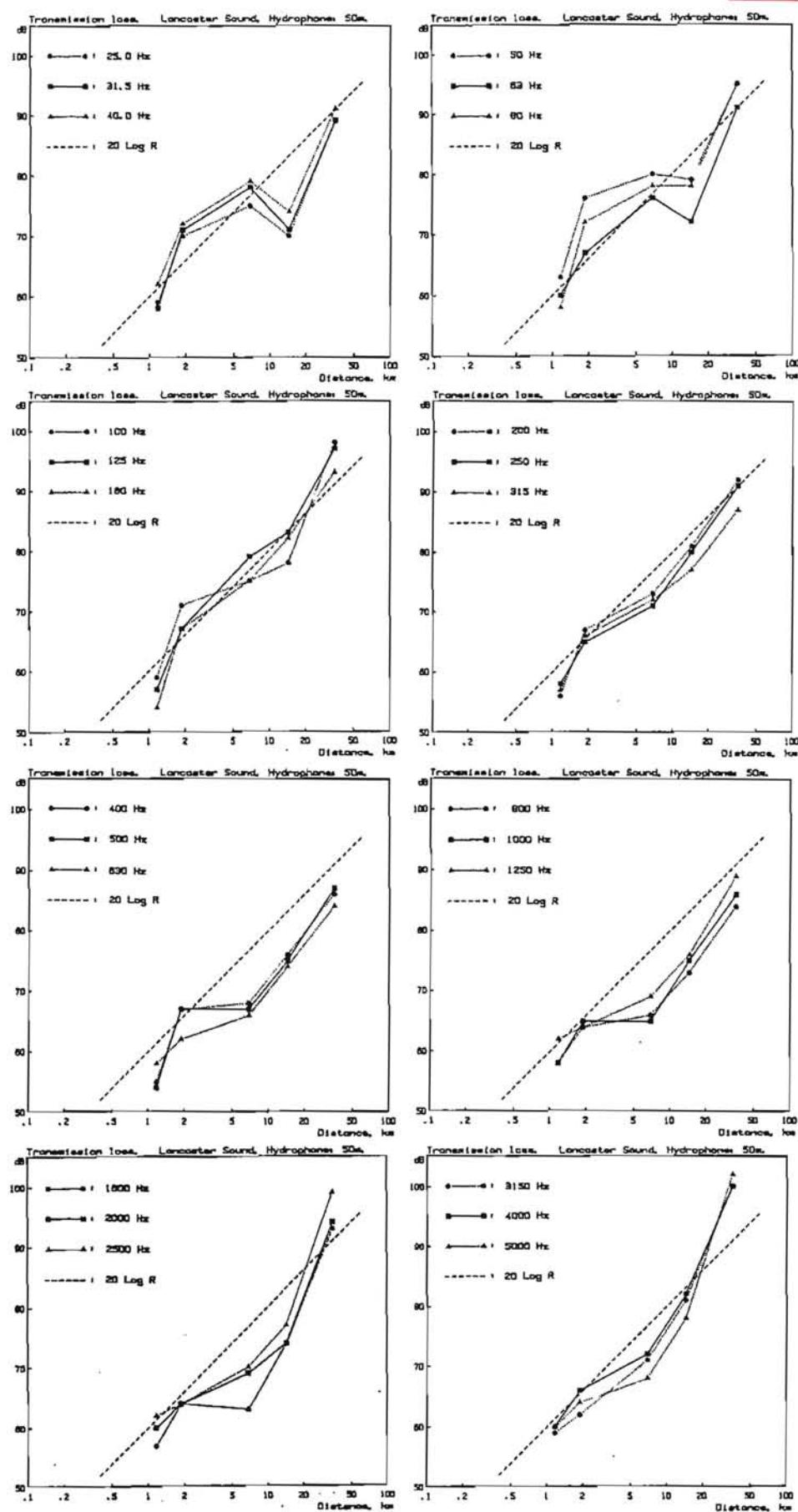


Figure 14.

Average sound transmission loss per 1/3-octave frequency bands versus distance. Lancaster Sound at Location B. Hydrophone depth 50 metres.



4.2 Measured Data Compared with Calculated Transmission Loss

To verify the results obtained by the transmission loss measurements a comparison with predicted transmission losses is performed in the following section. The predicted sound transmission loss is calculated by use of a "Fast Field Programme" (FFP) based on a full wave equation model. Reference is made to Rasmussen and Vistisen, Ref. /18/.

The calculations have been performed with the input data given in Table 3, assuming a source depth of 4 metres and a receiver depth of 50 metres. The water column and the subsurface is divided into layers with varying sound velocities and attenuation. Data about the actual geology of the subsurface in the area are very scarce and the values given in Table 3 are therefore estimated from experience acquired from other similar areas.

Depth (m)	Velocity (m/s)		Attenuation (dB/λ)		Density (kg/m ³)	Layer
	Compr.	Shear	Compr.	Shear		
<u>Baffin Bay:</u>						
0-55	1440	0	0.0001	0.0	1000	Water
55-100	1445	0	0.0001	0.0	1000	Water
100-200	1448	0	0.0001	0.0	1000	Water
200-400	1454	0	0.0001	0.0	1000	Water
400-500	1800	0	2.0000	0.0	1500	Sediment
500-	5250	2500	0.5000	0.5	2600	Basement
<u>Lancaster Sound:</u>						
0-100	1438	0	0.0005	0	1000	Water
100-200	1442	0	0.0005	0	1000	Water
200-300	1448	0	0.0005	0	1000	Water
300-400	1454	0	0.0005	0	1000	Water
400-600	1466	0	0.0005	0	1000	Water
600-700	1800	0	2.0000	0	1500	Sediment
700-800	2200	800	1.000	0.5	1800	Sediment
800-	5250	2500	0.5000	0.5	2600	Basement

Table 3.
Input data for the FFP sound transmission loss calculations.

In Table 3 it can be seen that the attenuation in water is a factor 5 higher for Lancaster Sound than for Baffin Bay. This increase has been introduced in order to compensate for the extra losses occurring in Lancaster Sound due to the heavier ice condition which results in increased scattering losses.

The results of the sound transmission loss calculations are presented in Figures 15, 16, and 17.

In Figures 15 and 16 the frequency dependence of the calculated sound transmission loss is illustrated for the frequency range 0-500 Hz. In Figure 15 the calculated results are compared with the measured results from Baffin Bay at a distance of 18 km. In Figure 16 the calculated results from Lancaster Sound are compared with the measured transmission loss at a distance of 15 km.

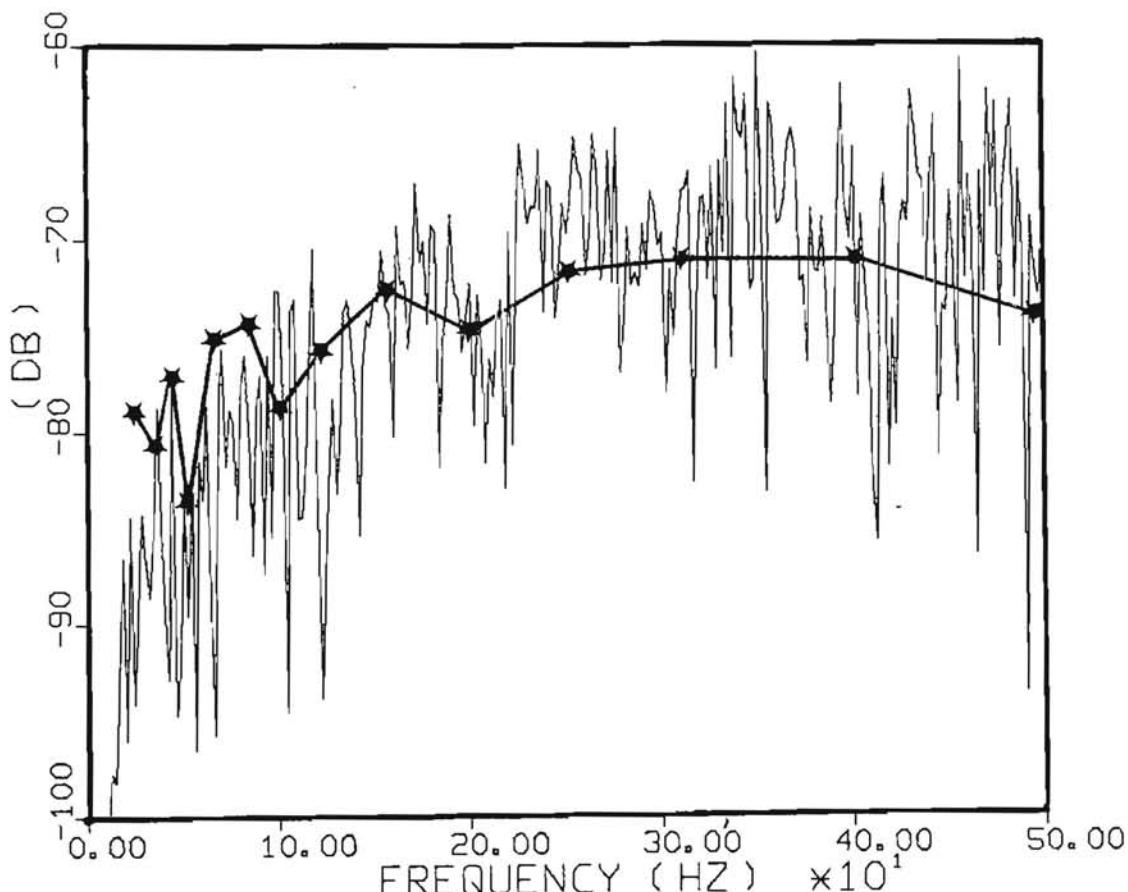


Figure 15.
Calculated sound transmission loss in the frequency range 0-500 Hz for the Baffin Bay conditions at a distance of 18 km. The actually measured losses in 1/3-octaves are marked with ★★.

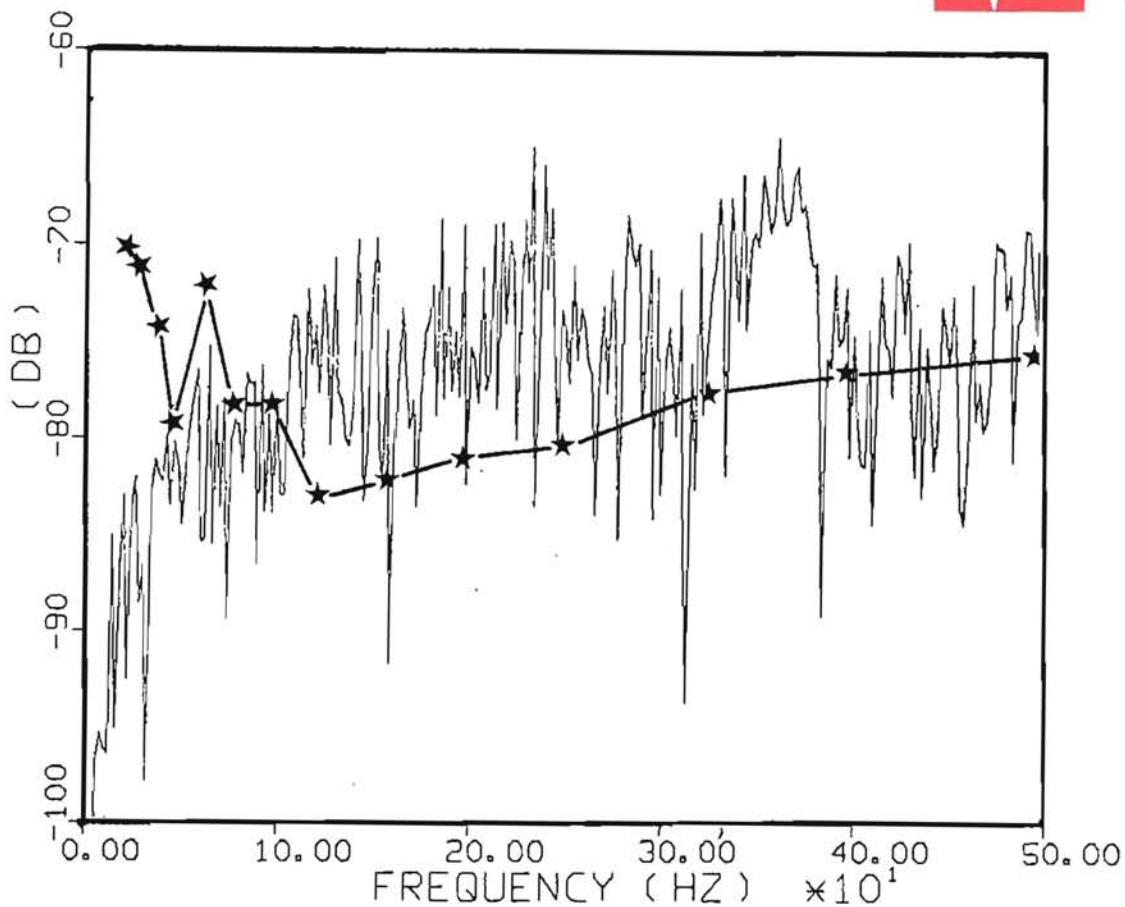


Figure 16.

Calculated sound transmission loss in the frequency range 0-500 Hz for the Lancaster Sound conditions at a distance of 15 km. The actually measured losses in 1/3-octaves are marked with ★★.

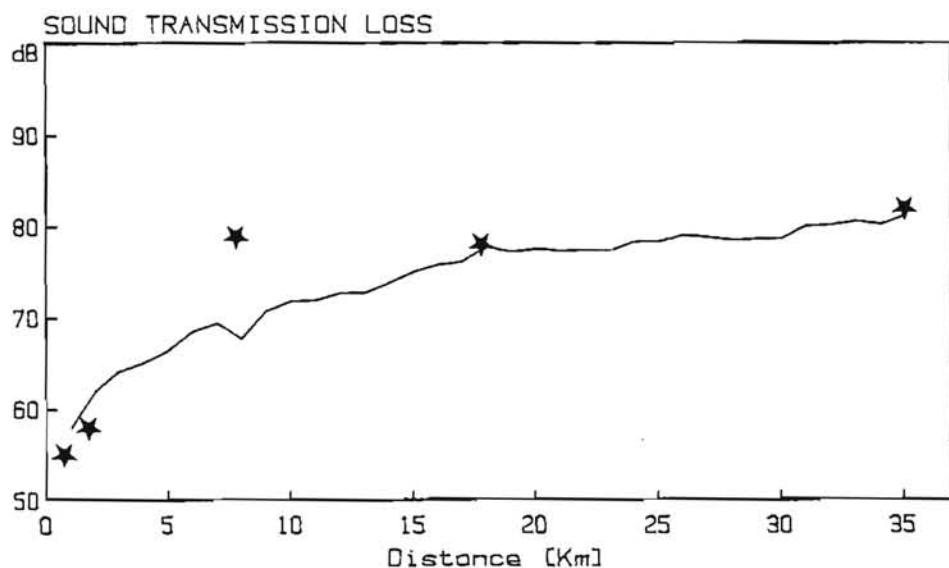


Figure 17.

Calculated sound transmission loss versus distance for the 1/3-octave with a centre frequency of 100 Hz for the Baffin Bay condition. The actually measured losses are marked with ★.



Figure 17 illustrates the variation in the calculated sound transmission loss with distance at the 1/3-octave frequency band with a centre frequency of 100 Hz. The calculations have been performed by calculating, for individual distances, the sound transmission loss in the frequency interval 89 Hz to 112 Hz corresponding to the 1/3-octave frequency band with a centre frequency of 100 Hz. The distances applied for the calculations have been 1, 2, 3, ..., 35 km. The sound transmission loss in the 1/3-octave frequency band has been found as an average on an energy basis of the calculated losses within the frequency band. The calculated transmission loss for Baffin Bay is compared with the corresponding results obtained from the measurements.

4.3 Discussion

The sound transmission loss measurements performed in Baffin Bay and Lancaster Sound illustrate the transmission properties in ice-covered waters over long distances. The results given in Figure 12 show that the transmission loss in Baffin Bay and Lancaster Sound is of the same magnitude at short distances while at the longest distances, the transmission loss is approximately 10 dB higher for the fast ice-covered Lancaster Sound condition than for the pack ice condition at Baffin Bay. This indicates an increased loss due to the rough interface between the ice-cover and the water which must be expected to be more pronounced in Lancaster Sound with the fast ice-cover than for Baffin Bay with the 5-8/10 ice concentration and no hummocked ice.

The effect of the receiver depth on the magnitude of the sound transmission loss can be seen in Figure 12 where the losses are generally higher at the shallow hydrophone (depth 5 metres) than measured at the deep ones. This effect is due to the phase difference between the direct arriving sound waves and the sound waves being reflected at the surface.

At low frequencies where the wavelength becomes large compared with the depth of the hydrophone, this phase difference will cause high losses even for the deep hydrophones.



The theoretically calculated transmission losses are of the same magnitude as the actually measured losses. However, it must be noted that the acoustical properties of the subsurface are important for the transmission loss calculations and that information about these parameters is scarce for the areas where the measurements have been conducted. For Baffin Bay it can be seen that the measured and calculated losses correspond well except in Figure 17 at the distance 7.8 km where a difference of approximately 10 dB occurs. The large difference is influenced by a high measured loss at 100 Hz compared with the neighbouring 1/3-octave.

The calculated transmission loss for Lancaster Sound at a distance of 15 km, given in Figure 16, does not fit very well with the measured data. At low frequencies the measured losses are lower than the calculated while they are higher at frequencies between 100 Hz and 300 Hz. The reason for the high measured losses in the mid-frequency region is probably the influence of the ice-cover. The presence of the ice-cover is modelled in the calculation by applying an attenuation of $0.0005 \text{ dB}/\lambda$ which is a factor 5 higher than for normal sea water. This attenuation has been selected from the results of other sound transmission studies in ice covered waters. However, this is a simplification and the difference between measured and calculated losses indicates extra losses which are not included in the prediction model.

5. RESULTS OF SHIP RADIATED NOISE MEASUREMENTS

The results given in this section are the underwater noise levels actually measured at a distance from the icebreaker and they have not been corrected with the transmission loss to obtain source levels. This part will be described in Section 6.

5.1 Frequency Content

The underwater noise radiated by the icebreaker will be generated by many different sound sources, such as propellers, diesel engines, various auxiliary machinery and pumps. Furthermore, the

breaking of ice will generate noise partly because of interaction between the ice cover and the hull of the ship, and partly when small pieces of ice are sucked down with the water to the propellers and thereby impacting the propeller blades.

The dominating noise contributions from machinery and propellers can be determined from a frequency analysis of the recorded underwater noise. Figures 18, 19 and 20 illustrate the narrow-band frequency spectrum of the underwater noise measured at 50 metres depth with three different load conditions for the icebreaker. The three load conditions occurring during ramming have been selected as these are very well defined. The nominal power and revolutionary speed are given in Section 6.2, Table 4.

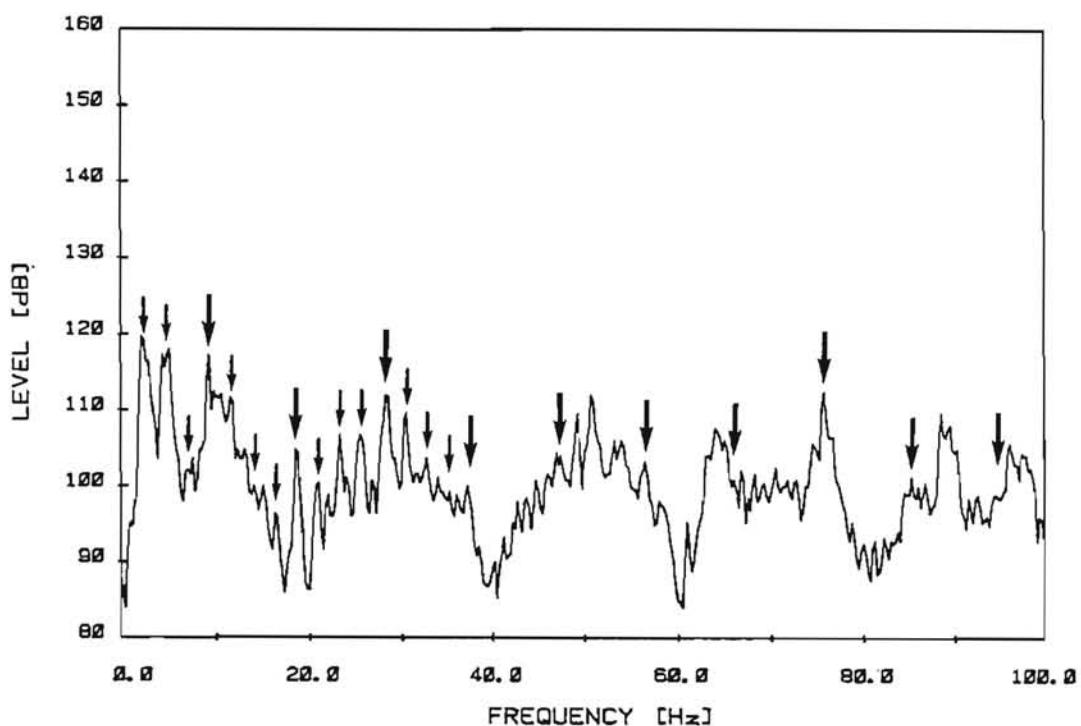


Figure 18.

Narrow-band frequency spectrum of the ship noise measured at Location B in Lancaster Sound at a distance of approx. 1.2 km. Load: high power ahead.

- Large arrows: harmonics of blade pass frequency.
- Small arrows: harmonics of revolutionary frequency.

Figure 18 shows that the radiated noise consists of broad-band noise super-imposed with discrete frequency components.

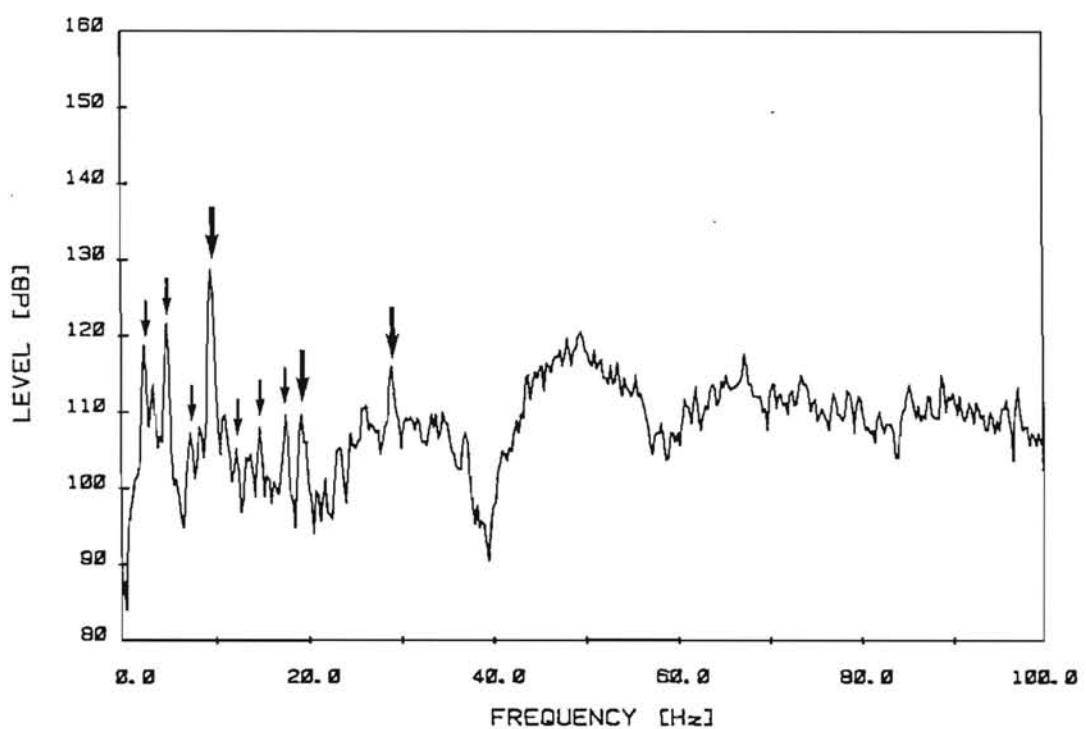


Figure 19.

Narrow-band frequency spectrum of the ship noise measured at Location B in Lancaster Sound at a distance of approx. 1.2 km. Load: high power astern.

- Large arrows: harmonics of blade pass frequency
- Small arrows: harmonics of revolutionary frequency.

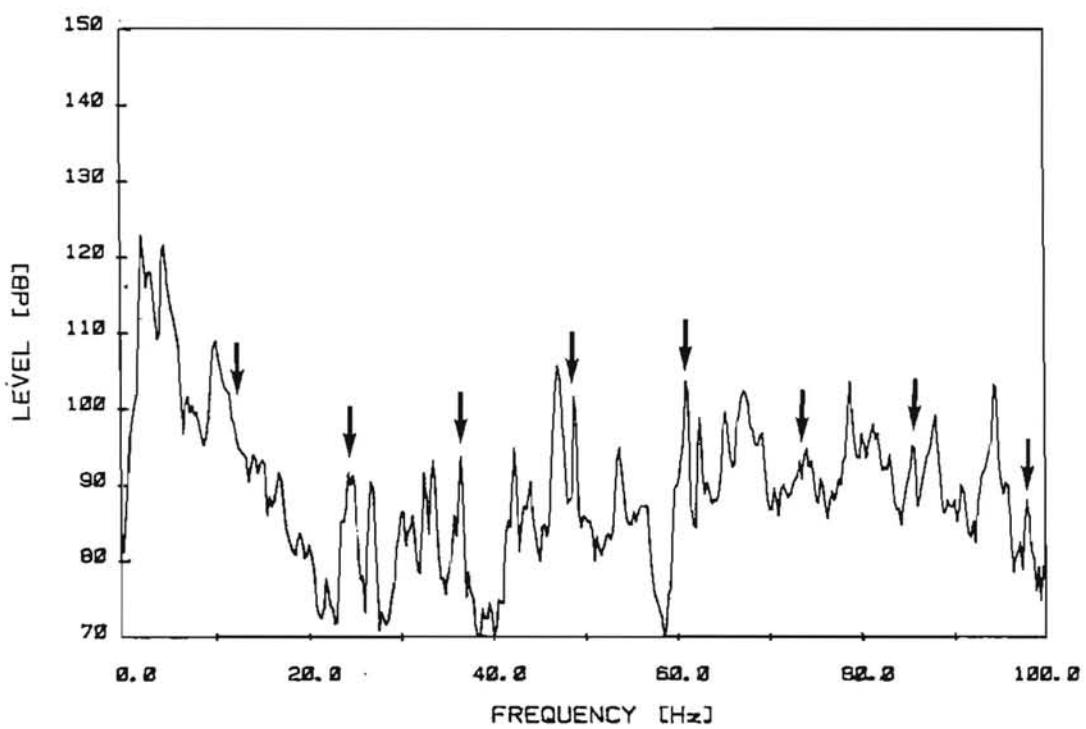


Figure 20.

Narrow-band frequency spectrum of the ship noise measured at Location B in Lancaster Sound at a distance of approx 1.2 km. Load: Idle.

- Large arrows: diesel generator components.



The broad band noise is generated by the propeller cavitation. The discrete frequency components are tonals generated by the propeller blades passing the wake field. The small arrows indicate harmonics of the revolutionary frequency, 2.38 Hz, corresponding to a revolutionary speed of 143 rpm. The large arrows indicate harmonics of the propeller blade pass frequency 9.5 Hz corresponding to the number of blades (4) multiplied by the revolutionary frequency. The repeated dips at multiples of 20 Hz which can be seen in Figure 18 are caused by the sound transmission from the ship to the receiver hydrophone when interaction between different transmission paths occurs.

When Figure 18 is compared with Figure 19, it can be seen that the broad band cavitation noise is 10-15 dB higher during the astern condition. The first blade pass frequency, which is 9.75 Hz (corresponding to 146 rpm) during astern, is approximately 10 dB higher while the other discrete frequency components are of the same magnitude.

It is not possible to detect any frequency components generated by the machinery in Figures 18 and 19.

In Figure 20 the noise, recorded with the ship in the idle condition, is given. During this load condition, the propellers were not loaded and the noise is therefore dominated by contributions from the diesel machinery. The arrows indicate harmonics of the revolutionary frequency, 12.25 Hz, corresponding to 735 rpm for part of the main diesel generators. The other components not marked with arrows are probably generated by other of the main diesel generators running at different speeds. The variable speed of the three sets (3 x 3) of main diesel generators makes it difficult to identify all components.

The auxiliary diesel generators are operated at a fixed speed of 720 rpm and the frequency of the components generated by this source will therefore be constant. However, these components cannot be detected in the frequency spectra.



The noise contribution generated by the icebreaking cannot be determined from the frequency analysis. This problem is discussed further in Section 5.3.

5.2 Variation of the Noise with Distance

The actually measured noise at different distances from the ice-breaker is illustrated in Figures 21, 22 and 23 for the three locations. The frequency spectrum of the recorded noise at three distances from the ship during operation at high load ahead at Locations A and B are given in Figures 21 and 22. The nominal load conditions are given in Table 4, Section 6.2. Figure 23 illustrates the spectrum of the noise at Location C during operation of the icebreaker at high power astern at a distance of 55 km. For comparison the ambient noise level is also given. From Figure 21 it can be seen that the noise recorded at Location A at a distance of 35 km is dominated by the ambient noise at frequencies above 250 Hz. At the distances shorter than 35 km, the ship generated noise is dominating in the whole frequency range shown, 25-5000 Hz.

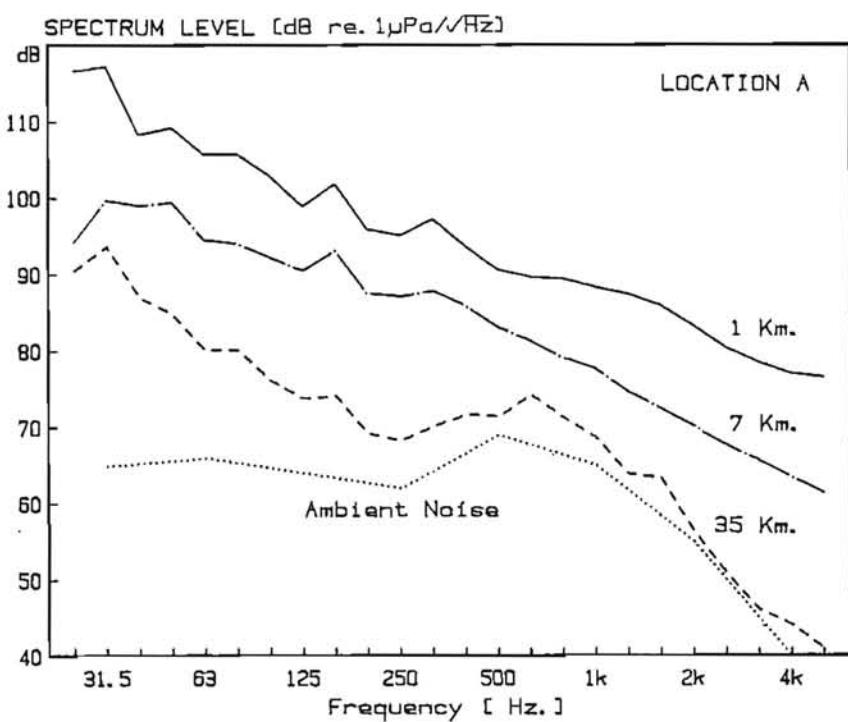


Figure 21.

Frequency spectra of the noise recorded at 1, 7 and 35 km from the icebreaker during a high power ahead condition. Location A in Baffin Bay, hydrophone depth: 50 metres.

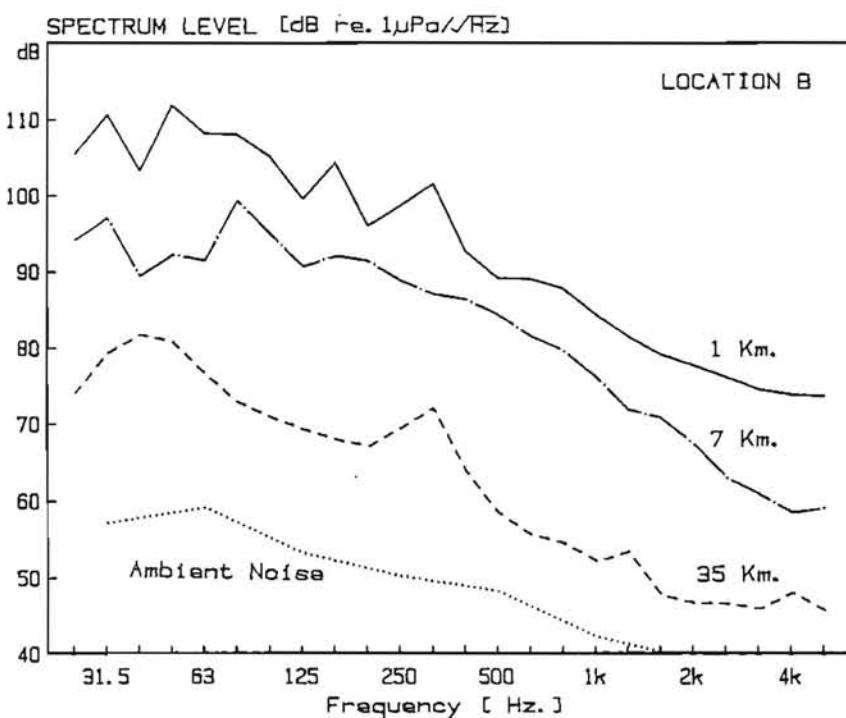


Figure 22.
Noise level recorded at 1, 7 and 35 km from the ice-breaker during a high power ahead condition. Location B in Lancaster Sound, hydrophone depth: 50 metres.

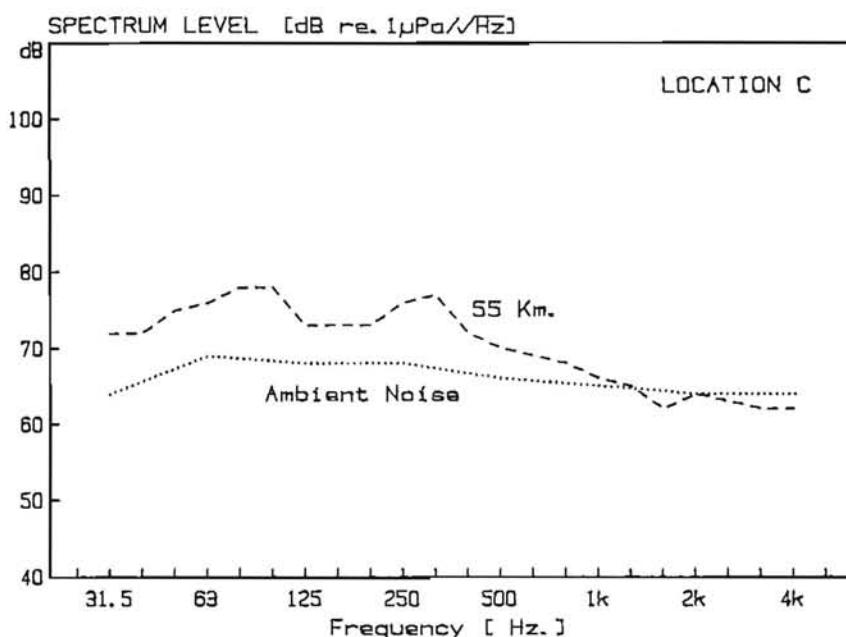


Figure 23.
Noise level recorded at 55 km distance from the ice-breaker during a high power astern condition. Location C in Lancaster Sound, hydrophone depth: 9 metres.



In Figure 22 it can be seen that the ambient noise at Location B is so low that even at the distance of 35 km from the icebreaker, the recorded noise is dominated by the ship generated noise.

The recordings performed at the ice edge in Lancaster Sound, Location C, which is illustrated in Figure 23, show that even at a distance of 55 km and with a rather high background noise level, then the noise generated by the icebreaker can be detected clearly at low frequencies. It should be noted that the high power astern, which is the most noisy condition, has been used in Figure 23.

5.3 Variation of the Noise with Load and Sailing Conditions

The load conditions of the ship during the measurements at Location B in Lancaster Sound were very well defined as the icebreaker due to the heavy ice conditions was operating in a "ramming" mode. During ramming the ship is not able to progress continuously through the ice cover and it is therefore necessary for the ship to operate as follows:

- 1) The propellers are operated with reversed revolutions and the ship moves astern in the open channel.
- 2) The propellers are stopped and the ship slowly decreases its speed astern in the channel in an idle condition.
- 3) The propellers are operated at high power ahead and the ship is accelerating to the end of the broken channel.
- 4) The ship is at high speed impacting the ice cover at the end of the channel.
- 5) With the propellers still operating at high power ahead, the speed of the ship is gradually decreasing to zero.
- 6) The loads of the propellers are changed to high power astern and a new cycle can begin.

This cycle is repeated again and again while the icebreaker makes stepwise progress. The progress made during each cycle was typically in the range of 50-100 metres but very dependent on the ice conditions.



The variations in the noise level with the load conditions are illustrated in Figure 24 during ramming operation of the ice-breaker in Lancaster Sound. In order to determine the load conditions of the ship, the signals recorded with the two accelerometers on board are given for the same time interval. The time axis is made comparable by correcting the accelerometer signals with the transmission time corresponding to the distance between the icebreaker and the measurement site.

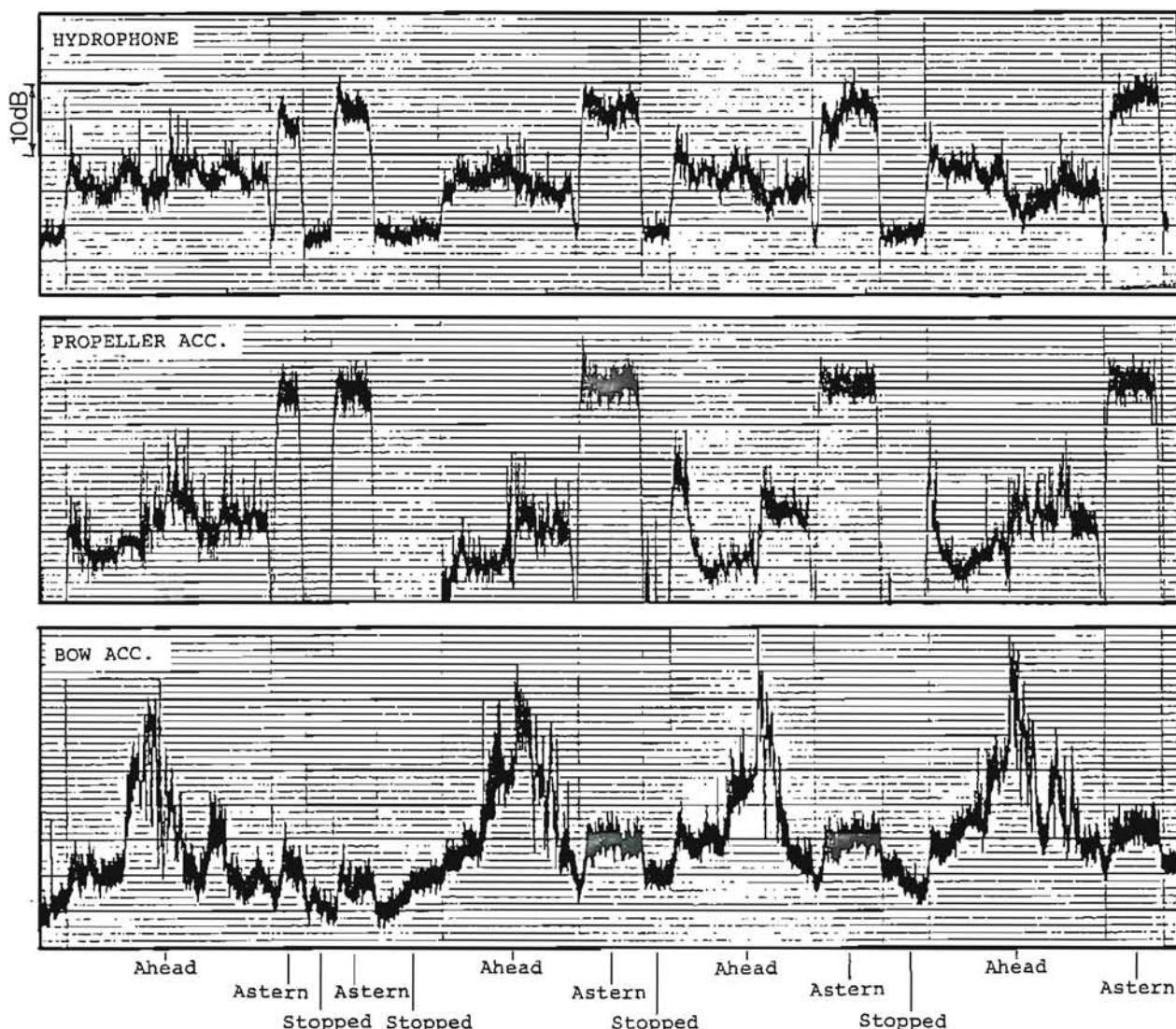


Figure 24.

Variation of the underwater noise signal compared with the accelerometer signals used to monitor the periods with different load conditions. The hydrophone signal is the overall level 20-5000 Hz measured in Lancaster Sound during four ramming periods.



Figure 24 illustrates how the underwater noise level varies with the load condition. In the reverse mode the noise level is approximately 10 dB higher than during the ahead condition and 20 dB higher than during the idle condition.

The propeller load condition can be read from the propeller accelerometer signal which shows pronounced peaks at the reverse condition and very low levels during idle condition. During the ahead condition the vibration level measured close to the propeller varies, with high levels in the start of the acceleration, lower levels when the ship is increasing its speed and high levels again when the ship is breaking ice and decelerating.

The vibration signal from the bow accelerometer clearly indicates the periods with icebreaking. Such periods are characterized by maximum levels when the icebreaker reaches the end of the broken channel at high speed and starts breaking ice, and decreasing levels when the speed decreases to zero.

An indication of the amount of noise generated by the icebreaking itself due to the impact on the shell plating caused by the ice-cover can be found from Figure 24. It is observed that the hydrophone signal does not increase in the periods when the ship is breaking ice. This indicates that the icebreaking itself does not contribute significantly to the received underwater noise signal at a distance from the ship. The reason for this is probably that the icebreaking noise is generated by sources located in or close to the surface, which means that the "pressure release effect" will result in reduced radiation to the water.

The pulses in the hydrophone signal occurring occasionally during the sailing ahead condition are probably generated by pieces of ice impacting the propellers as the same pulses appear in the propeller accelerometer signal but not in the signal from the bow accelerometer.



5.4 Discussion

The frequency content of the recorded ship noise shows that the dominating noise source of the ship is propeller cavitation. This noise contribution can be seen as broad band noise at frequencies above approximately 50 Hz. The highest cavitation noise occurs when the propellers are operated at reverse revolutions. In this condition the propeller blade profiles become reversed relatively to the water flow and heavy cavitation is to be expected.

At lower frequencies discrete frequency components are dominating. These components are generated by the propeller blade passing in the wake field. The highest levels occur at the blade pass frequency and its harmonics.

In the idle condition the noise is dominated by discrete frequency components generated by the machinery. These components are seen at harmonics of the revolutional frequency of the 4-stroke main diesel engines. The revolutional rate of the main diesel generators, supplying DC power for the propulsion motors, will vary with the load and the frequency of the pure tone components will therefore depend on the power consumption. As the propulsion motors are not necessarily operated at the same revolutional speed there will be many different discrete frequency components in the spectra of the recorded noise, depending on the revolutional speed of the individual engines.

The curves given in Figures 21, 22 and 23 in Section 5.2 illustrate the impact of the ship noise on the natural marine environment. The curves show the measured ship noise compared with the ambient noise at distances up to 55 km away from the ship. At Location A, where the ambient noise was quite high due to the sounds from bearded seals, the ship noise during a sailing ahead condition could be detected 35 km away at frequencies below



500 Hz. The ship noise measured 35 km away was higher than the ambient noise level in the entire frequency range 20-5000 Hz at Location B due to the low ambient noise level.

At Location C, 55 km away from the ship, the noise generated by the ship in an astern condition exceeded the ambient noise level by approximately 10 dB at frequencies below 800 Hz.

A comparison between the measured underwater noise signal and the signals from two accelerometers, used as indicators of the load condition, is shown in Figure 24. The curves illustrate how the noise level depends on the load condition with the maximum noise generated during an astern condition and low noise during idle when the propellers are stopped. During sailing ahead the noise level is highest at low speeds and during icebreaking.

The most important result found from Figure 24 is probably that the noise generated by the icebreaking itself does not contribute significantly to the overall noise level measured at a distance from the ship. The reason is most likely that the icebreaking noise is generated by sources located close to the surface, such as the ice cover impacting the hull of the ship, the actual breaking of the ice and the interaction between individual pieces of ice. The radiation of noise generated close to the surface will be highly attenuated due to phasing between the direct and the surface reflected waves, the so-called "pressure release effect".

Another aspect of the noise generated by the icebreaking is the additional noise generated by the propeller due to small pieces of ice present in the water stream which impacts the propeller blades. This condition will cause strong wear on the propeller blades and the construction of icebreakers is therefore designed with the particular aim of avoiding this problem. However, it must be expected that pieces of ice will hit the propellers occasionally. In Figure 24 the pronounced peaks in the hydrophone signal occurring occasionally during sailing ahead are probably such events.



6. ESTIMATED SOURCE LEVELS

The noise measured at a distance from a ship is depending on the sound transmission loss at the particular measurement site. This loss will be determined by the location but also by the immersion of the main sound sources of the ship, such as propellers and machinery. In order to compare the noise obtained for a specific ship with data from other ships, measured or calculated, it is convenient to define a "source strength", as described below, which is independent of the transmission properties and the immersion of the source.

6.1 Source Strength Definition

The source strength of the underwater noise generated by a ship is commonly expressed as the noise level that would be measured at a distance of one metre from an equivalent monopole source, placed at the acoustic centre of the noise sources of the ship and with an acoustic power output similar to the generated noise. The source level is found by adding the measured transmission loss to the level of the received noise signal at certain distances to the ship.

The equivalent monopole source strength can thus be expressed as the sound pressure level per 1/3-octave frequency band, referring to one metre distance from the acoustic centre of the source. The source strength can be calculated from:

$$L_s = L_p + TL \quad (1)$$

where

L_s is the equivalent source strength of the noise sources per 1/3-octave frequency band in dB re. $1 \mu\text{Pa}$.

L_p is the measured sound pressure level per 1/3-octave frequency band in dB re. $1 \mu\text{Pa}$.

TL is the sound transmission loss corresponding to the range in question.



6.2 Source Strength Calculated from Measured Data

From eq. (1) the equivalent monopole source strengths for the noise sources of the icebreaker sailing at different load conditions, have been estimated, applying the measured average transmission losses presented in Tables 1 and 2. The source strength has been determined in the frequency range 25 Hz - 5000 Hz.

The source strength has been determined for six different load conditions which are described in Table 4. During navigation in ice, it is normal that the load conditions are changed quite much. During this investigation the aim was to obtain a few specific load conditions where the load was kept constant. However, especially during the measurements in the pack ice in Baffin Bay some variations in the load have occurred and the revolutionary rates and power values given in Table 4 are average levels.

Load Condition	Location	Propeller rpm	Propulsion Power
Ahead	A, Baffin Bay	140	5.500 kW
Half power	A, Baffin Bay	110	2.500 kW
Low power	A, Baffin Bay	80	1.000 kW
Ahead, ramming	B, Lancaster Sound	140	10.000 kW
Astern, ramming	B, Lancaster Sound	140	10.000 kW
Idle	B, Lancaster Sound	0	0

Table 4.
Load conditions used for the source strength determination.



The approximate revolutional speed of the propellers represent the average of the two wings and the centre propeller revolutional rate during several intervals for each load condition. The power load and rpm given for the ramming condition is found as an average of 6 cycles and read from the instruments in the engine control room.

The source strengths are determined as an average of measurements performed at many different distances for each load condition. For the measurements at Lancaster Sound the five different distances where the transmission loss was measured have been applied for the source strength determination. At Baffin Bay the source strength at full ahead, 1/2 power and low power have been determined as an average from 7, 3 and 4 different distances, respectively. The full astern condition at Baffin Bay only happened once and the source strength is therefore only determined at a single distance.

The measured average source strengths are presented in Figures 25 and 26 for the Baffin Bay and the Lancaster Sound conditions, respectively.

Note that the 1/3-octave frequency bands contains contributions from both discrete frequency components and broad band noise.

The pure tone components dominate at low frequencies while the board-band noise is present at high frequencies where propeller cavitation occurs.

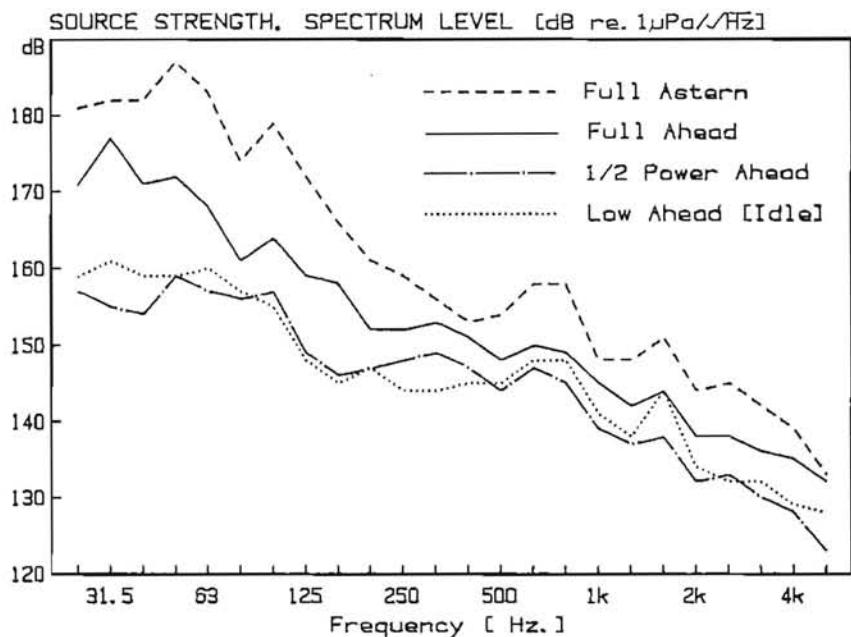


Figure 25.

Source strength measured at Location A, Baffin Bay during full ahead, half power, low power and full astern.

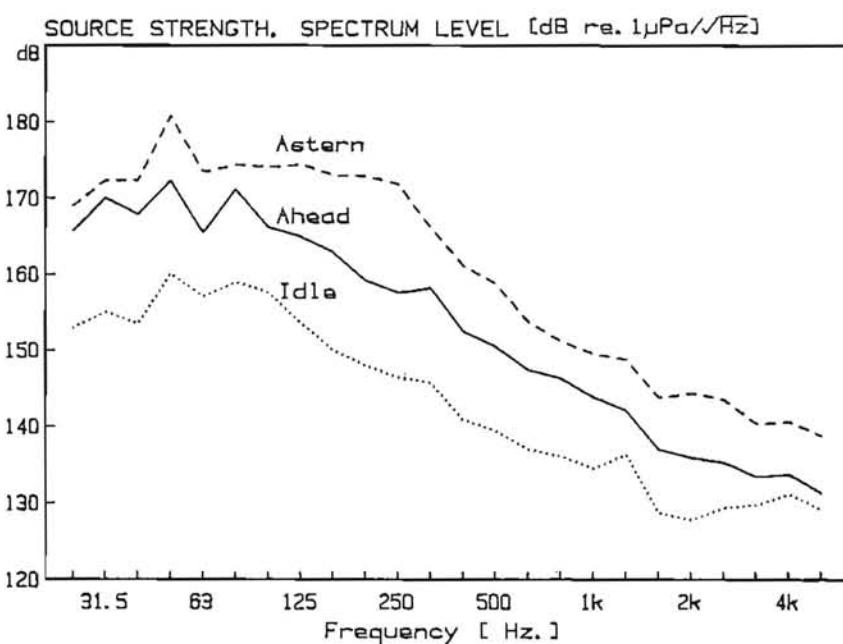


Figure 26.

Source strength measured at Location B, Lancaster Sound during ramming at full ahead, full astern and idle.



6.3 Measured Source Strength Compared with Data from Prediction Models

Based on theoretical models, the radiated underwater noise from a ship can be predicted. As can be seen in Sub-section 5.1 the dominating noise source is the propeller. In the previous investigations, Ref. /9/ and /5/, it was found that the model derived by N. Brown, Ref. /7/ was in good accordance with measured data. The radiated underwater noise from the propeller is by this model predicted from:

$$L_S = K + 40 \log(D/1 \text{ m}) + 30 \log(n/1 \text{ Hz}) + 10 \log(B) \\ - 20 \log(f/1 \text{ Hz}) + 10 \log(A_C/A_D) \quad (2)$$

where:

L_S is the spectrum level in dB re. $1 \mu\text{Pa}/\sqrt{\text{Hz}}$.

K is 163 dB for open propellers and 170 dB for nozzle propellers.

D is propeller diameter.

n is propeller revolutional rate in rev./sec.

B is number of propeller blades.

f is frequency.

A_C is the swept area of cavitation.

A_D is disc area of the propeller.

Eq. (2) applies to the frequency range above the peak frequency of the spectrum which, according to N. Brown, can be determined from:

$$f_p = \frac{1100}{D} \frac{U}{U_i}^{-2/3} \quad (3)$$

where:

$\frac{U}{U_i}$ is the ratio of the actual propeller speed to the cavitation inception speed



Based on the results of the previous investigations Ødegaard & Danneskiold-Samsøe has stated that the peak frequency should be lowered in order to fit the measured data better. It is suggested that the peak frequency should be determined by:

$$f_p = \frac{550}{D} \left(\frac{U}{U_i} \right)^{-2/3} \quad (4)$$

In Table 5 the estimated values of the cavitation parameters are presented for the various load conditions for the icebreaker.

Condition		U/U _i		A _C /A _D
<hr/>				
Full ahead, ramming mode		3.0		0.5
Full astern, ramming mode		5.0		0.9
Full ahead, pack ice		2.0		0.3
Half power ahead, pack ice		1.5		0.2
Low power ahead, pack ice		1.0		0.1
<hr/>				

Table 5.
Estimated cavitation parameters used for the prediction
of propeller noise generated by the icebreaker.

In Figures 27, 28, and 29 the measured source strengths are compared with the predicted propeller noise levels for different load conditions. The predicted levels are found from Eq. (2) and Eq. (4) applying the cavitation data given in Table 5.

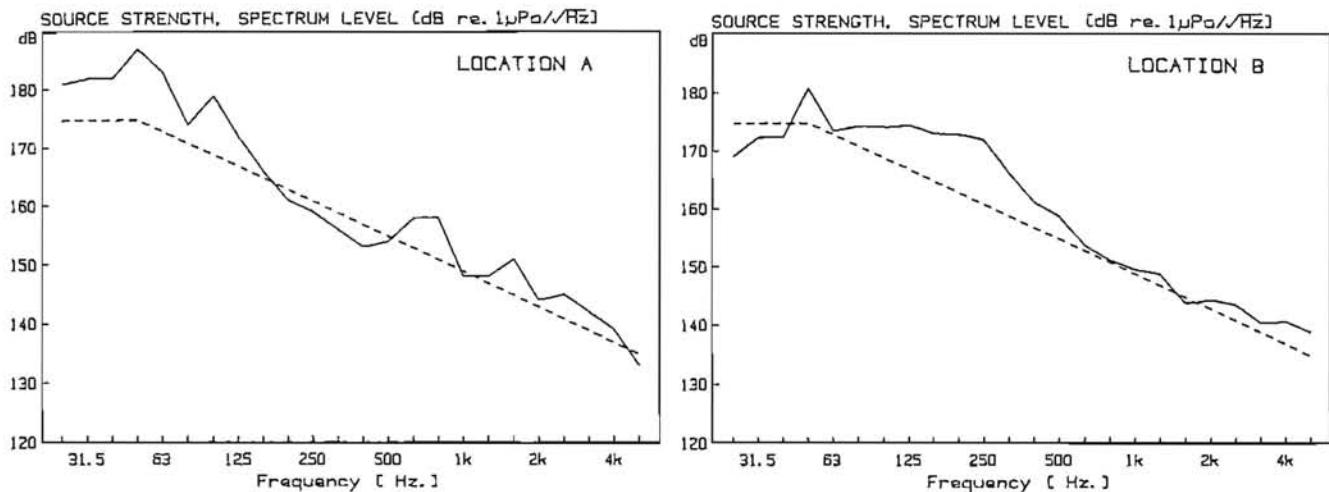


Figure 27.
Measured source strength compared with predicted levels
for the icebreaker sailing with a high power astern
condition at Location A and Location B.

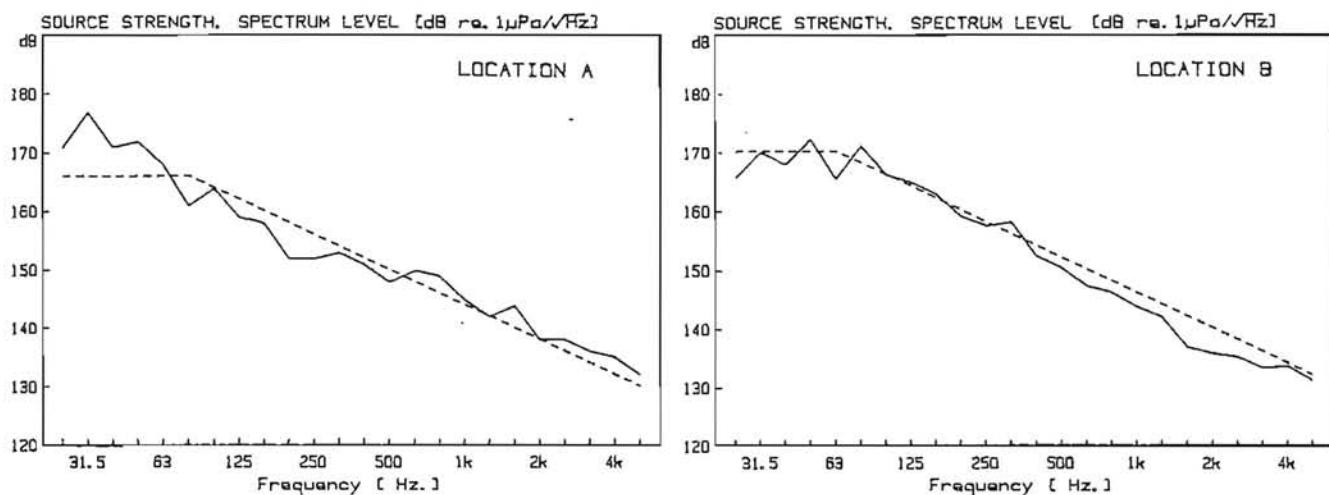


Figure 28.
Measured source strength compared with the predicted
source strength of the icebreaker sailing with high
power ahead in the pack ice of Baffin Bay and in the
ramming condition in Lancaster Sound.

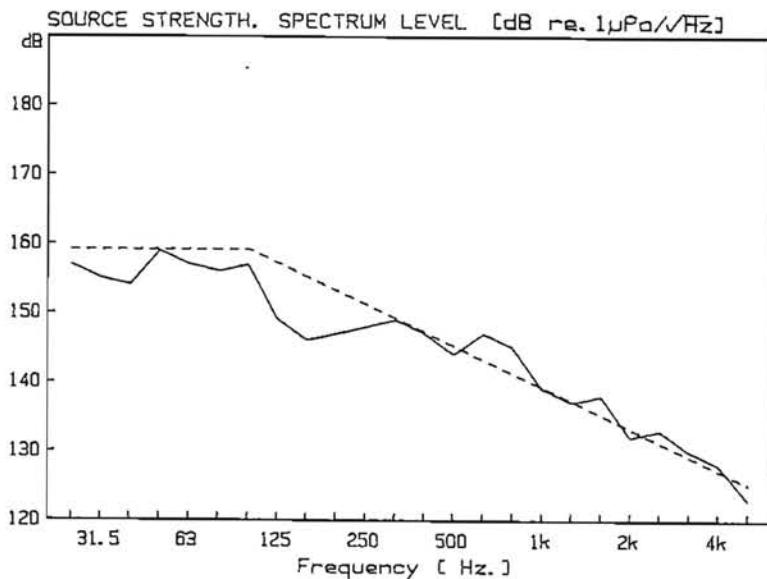


Figure 29.

Measured source strength compared with the predicted source strength for the icebreaker sailing at 1/2 power ahead in the pack ice of Baffin Bay.

6.4 Results compared with Data from an Open Water Measurement

The noise radiated from the "John A MacDonald" has been measured during open water conditions on a naval Sound Range in Halifax. The measurements were performed by the "Defence Research Establishment Atlantic" (DREA) and the results have been reported by Leggat, ref. /12/. The aim of the DREA investigation was to compare the results obtained during operation of the ship in open water with the present results from ice covered areas in order to evaluate the amount of noise generated by the icebreaking itself.

During the sound range measurements, 9 different load conditions were tested. In Figures 30, 31 and 32 the results from three of these load conditions are compared with the results obtained in Baffin Bay and Lancaster Sound.

Figure 30 shows the free field source strength for the low load ahead condition. During the sound range measurements the revolu-



tional rate was 110 rpm for all three propellers, power 2473 kW and speed 12.4 Knots. The broken line represents the source strength for the similar load condition during the measurements in Baffin Bay (Location A). For comparison the dotted line represent the "full" ahead also from Location A. It can be seen that the highest source strength occurs during the sound range measurement even when compared with the full load condition.

In Figure 31 the source strength spectra for the ahead conditions with higher loads are given. The sound range measurements were performed with a revolutionary rate of 130 rpm, a power of 4361 kW and a speed of 14.5 Knots. The result from the sound range is compared with the results obtained at the high power ahead conditions from Location A and Location B. Again the source strength measured on the sound range is higher than the corresponding levels measured in the ice.

Finally Figure 32 illustrates the source strength spectra during the astern condition. At the sound range this measurement was performed during a deceleration from 10 Knots ahead to stopped with a reversed revolutionary speed of 115 rpm for all three propellers and a power of 5644 kW. During the measurements presented in this report the astern condition was different as the ship was accelerating in an astern movement. This difference will result in a higher source level during the sound range measurement due to the very turbulent wake field which must be expected in this condition.

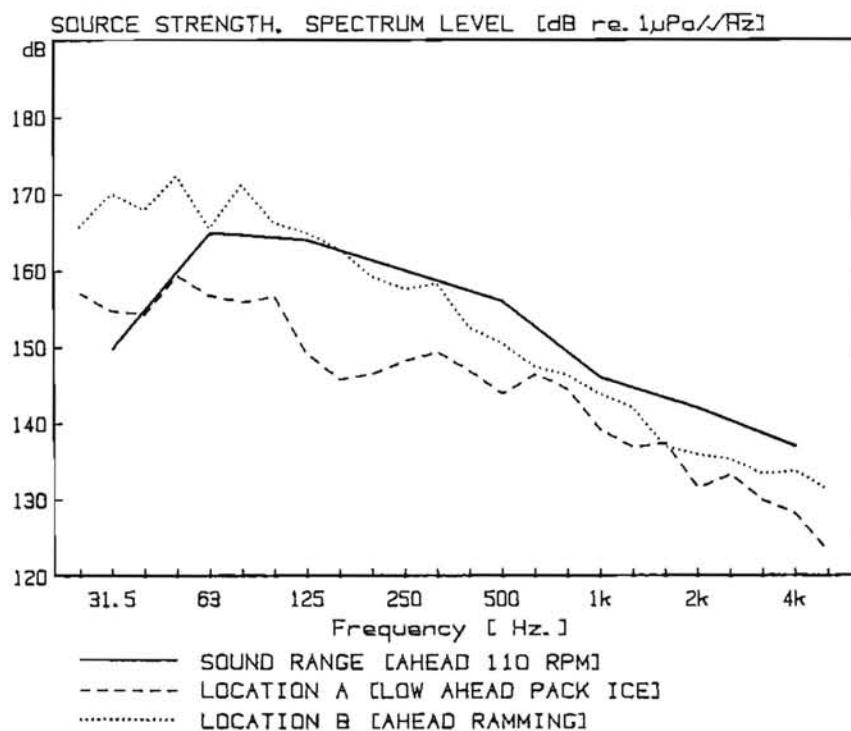


Figure 30.

Source strength of John A. MacDonald measured on a sound range compared with results from the measurements in Baffin Bay and Lancaster Sound.

Load condition: Low power ahead.

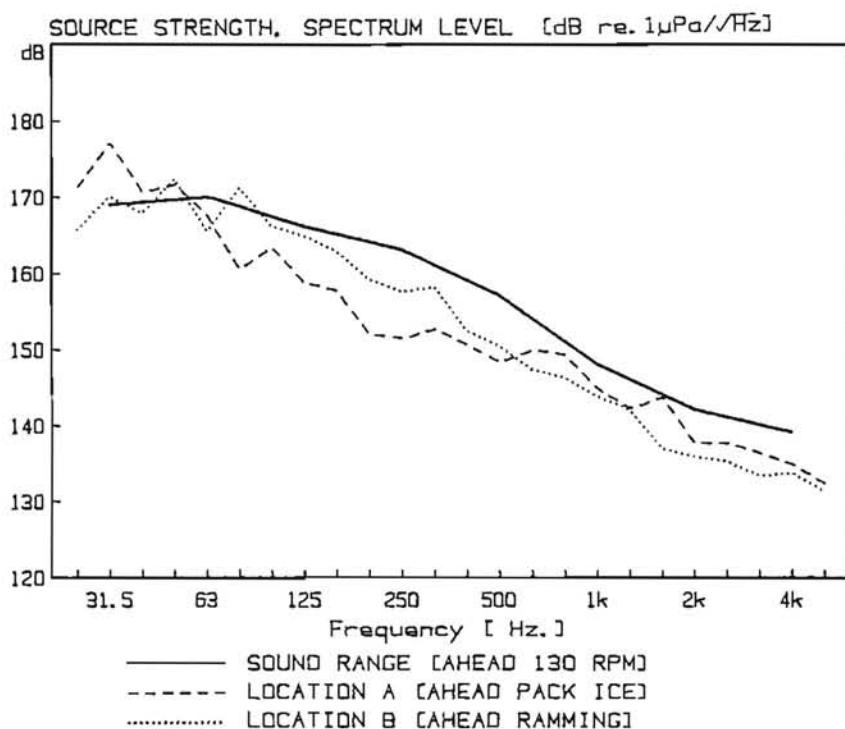


Figure 31.

Source strength of John A. MacDonald measured on a sound range compared with results from Baffin Bay and Lancaster Sound.

Load condition: High power ahead.

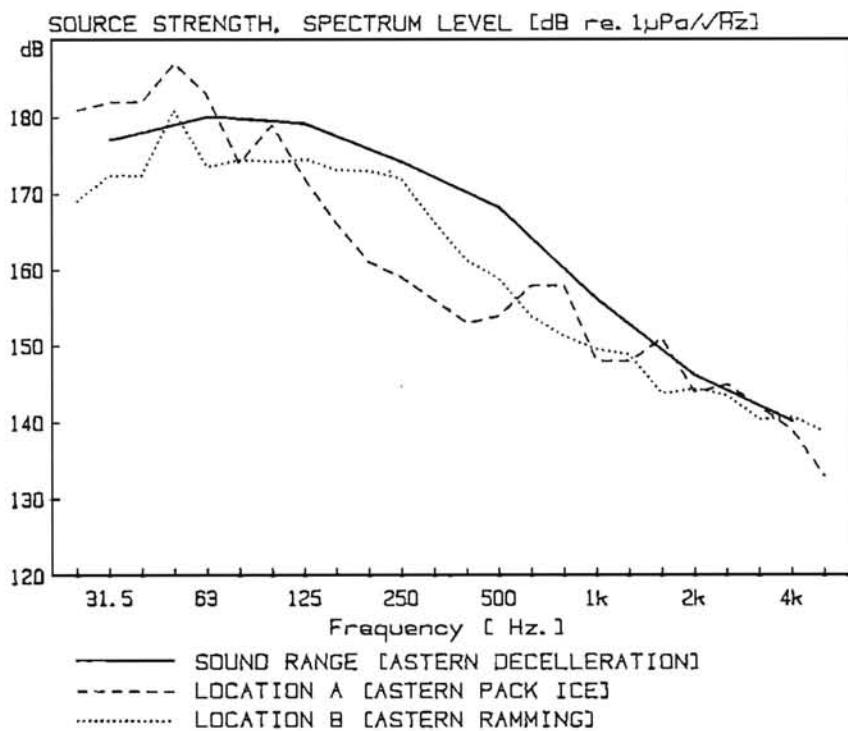


Figure 32.

Source strength of John A. MacDonald measured on a sound range compared with results from Baffin Bay and Lancaster Sound.

Load condition: Astern.

6.5 Discussion

The free field source strength of the noise radiated from "John A. MacDonald" has been determined for several different load conditions. The highest source strength occurs during the load condition when the icebreaker sails astern with reversed propeller revolutions.

The maximum source strength for the astern condition occurs in the 50 Hz 1/3-octave frequency band as seen in Figures 25 and 26. At higher frequencies the source strength decreases with approximately 6 dB/octave.

For the sailing ahead condition the maximum source strength is approximately 5-10 dB lower than for the astern condition with the highest difference at low frequencies.



In the idle condition when the propeller noise does not influence the spectra, the source strength is approximately 5-10 dB lower than during the ahead condition.

The measured source strength has been compared with data obtained from a prediction model. As the propeller is the dominating noise source during normal sailing conditions, the prediction model derived by Neal Brown for propeller cavitation noise has been applied. The break frequency, specified in the theory by Neal Brown, has been lowered by a factor 2 based on experience from previous measurements.

It can be seen from Figures 27, 28 and 29 that in general the measured source strength agrees well with the prediction model. In the astern condition, however, there is a tendency that the prediction model underestimates the radiated noise in parts of the frequency range with up to 10 dB as can be seen from Figure 27.

The measured source strength has also been compared with data obtained at a naval sound range with "John A. MacDonald" sailing with different load conditions in open water. This comparison shows that in general the source strength measured on the sound range is higher than the results obtained in Baffin Bay and Lancaster Sound during similar load conditions. In the astern condition, the higher source strength during the sound range measurements can be explained by the very turbulent wake field occurring when the ship is reversing the propeller revolutions during speed ahead. This was not the case during the astern conditions in Baffin Bay and Lancaster Sound where the ship was sailing astern.

The fact that the levels occurring in the ice covered areas are not higher than the levels in open water indicate that the breaking of the ice does not contribute significantly to the overall noise radiated from the ship as it is also found from the results discussed in Section 5.



7. DISCUSSION AND CONCLUSION

The underwater noise study performed from the icebreaker "John A. MacDonald" has resulted in new data about ambient noise, sound transmission loss, radiated ship noise and source strength.

The ambient noise measurements were performed in short intervals of time and therefore the results do not pretend to represent the variations in the ambient noise which occur with changes in weather and ice conditions. However, the data can be used together with results from other investigations in order to evaluate the natural acoustic environment in arctic waters.

The noise recorded in Baffin Bay was dominated by the sounds from bearded seals at frequencies above 250 Hz. Even inclusive of the sounds from the bearded seals, the magnitude of the recorded noise levels was within the range of the ambient noise levels recorded off Thule during another study.

Very low levels of ambient noise were recorded below the fast ice cover in Lancaster Sound. At this location there were no sounds of biological origin detectable in the noise signal. The magnitude of the noise was close to the detection limit of the highly sensitive hydrophone used and lower than previously measured off Cape York during similar ice conditions.

At the ice edge in Lancaster Sound the natural noise was dominated by sounds from the many marine mammals in this area. The sounds were mostly "click" sounds and moans resulting in a relatively flat spectrum. At low frequencies the noise from the ice-breaker working 55 km away exceeded the ambient noise in periods.

Two sound transmission loss measurements have been performed, both at five distances from 0.7 km to 35 km. At Baffin Bay the measurement site was placed in an area covered with pack ice with a concentration of 5/10-8/10 and a water depth of 400 metres. In



Lancaster Sound the area was covered with 2.5 metres of fast ice and the water depth was 600 metres.

The measured average transmission loss is generally of the same magnitude as found from spherical spreading at the short distances. At longer distances the measured loss tends to be lower than found from the simple spherical spreading model.

In general the sound transmission loss is higher at Lancaster Sound than at Baffin Bay probably due to the additional attenuation caused by the more concentrated ice-cover in Lancaster Sound. A maximum difference of approximately 10 dB between the losses measured at the two locations occur at the longest distance, 35 km.

The transmission loss measurements were performed with a constant source depth and three different receiver depths. In general the highest losses occur for the shallow receiver hydrophone as would be expected due to the surface effect. The difference is especially pronounced at long distances and low frequencies where the losses are up to 10 dB higher when measured with the hydrophone close to the surface than when measured with the deep ones.

The frequency analysis of the noise radiated from the ship show that the propellers are the dominating noise source of the ice-breaker. The propeller noise consists partly of discrete frequency components caused by pressure pulsations and partly by broad band cavitation noise. The noise generated by the machinery can only be detected during the idle condition when the propellers are stopped.

The noise generated by the ship during normal sailing conditions could be detected at long distances from the ship. The received noise level at the maximum distance of 35 km exceeds the ambient noise level by up to 20 dB when the icebreaker is sailing ahead



at high power and 140 rpm. Even at the ice edge in Lancaster Sound, 55 km away from the icebreaker, the noise generated during an astern condition exceeded the ambient noise level by up to 10 dB at low frequencies.

Simultaneously with the noise measurements, vibration measurements have been performed on board the icebreaker in order to monitor the load conditions used. The comparison between the hydrophone signal and the signals from the two accelerometers placed in the bow and in the vicinity of the propeller, illustrates how the total underwater noise level varies with the sailing conditions. As expected the highest overall noise level occurs when the icebreaker is sailing astern and the lowest levels occur in the idle condition. More important, this comparison indicates that the noise generated by the icebreaking itself does not contribute significantly to the noise level at a distance from the ship.

The explanation for this is probably that the ice breaking noise is generated in or very close to the surface. Consequently the radiation to the water will be significantly reduced due to the "pressure release effect" caused by the phase difference between the direct and the surface reflected sound waves.

In order to compare the noise generated by "John A. MacDonald" with other ships and prediction models, the source levels for different load conditions have been calculated. The free field monopole source strength is found by correcting the recorded ship noise with the measured sound transmission loss.

The highest source strength occurs during the load condition when the icebreaker is sailing astern with reversed propeller revolutions. Compared with the astern condition, the source strength is approximately 5-10 dB lower in the sailing ahead condition and 25 dB lower in the idle condition. Generally the shape of the



source strength spectra decreases by 6 dB/octave at mid and high frequencies.

The measured source strengths compare well with the expected source strengths found from the prediction model for propeller cavitation noise. The prediction model derived by Neal Brown has been modified by lowering the break frequency with a factor 2 based on experience from previous measurements.

Results on radiated noise from John A. MacDonald sailing in open water have been reported by "Defence Research Establishment Atlantic" based on measurements on a naval sound range. The comparison between these data and the present results shows that the source strength is generally somewhat higher when measured on the sound range in open water than measured in the ice-covered area. Consequently, this comparison also indicates that the breaking of the ice does not contribute significantly to the overall noise radiated from the ship.

Finally, it can be concluded that the noise study performed from the John A. MacDonald has resulted in valuable data which can be used in the evaluation of future shipping in arctic areas.

It has been found that the ambient noise can be very low as measured in Lancaster Sound (Location B) and that the ship generated noise can influence the marine acoustic environment at long distances from the ship as measured at the ice edge 55 km from the ship.

Furthermore, the results indicate that the noise generated by the breaking of ice is not significant compared with the cavitation of the propellers. As the prediction models for propeller cavitation noise fit the measured data quite well, it seems to be possible to predict the source strength from icebreaking ships with a reasonable accuracy.

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APPENDIX A

Data for the "JOHN A. MACDONALD"



The icebreaker "JOHN A. MACDONALD" was built by Davie Shipbuilding Ltd. in 1960. The ship is owned by the Canadian Coast Guard and operates with icebreaking and supply work in Canadian waters. The main data for the ship are as follows:

Length overall	: 110 metres
Breadth Mld.	: 21.3 metres
Maximum draft	: 8.6 metres
Dead weight	: 3685 tons
Speed	: 15.5 knots

The propulsion plant is diesel electric, consisting of 9 Fairbanks-Morse opposed piston, non-reversing diesel engines each connected to a Westinghouse generator. Each of the 3 propellers is driven by a Westinghouse electric propulsion motor. The main data for the propulsion plant are as follows:

Diesel Engines

Manufacturer	: Canadian Locomotive Co. Ltd.
Type	: 38D8-1/8 x 12
No. of cylinders	: 12
Power	: 1470 kW = 2000 BHP
Rotational speed	: 750 rpm
Mounting	: Solidly connected to the foundation

Generators

Manufacturer	: Canadian Westinghouse Co. Ltd.
Power	: 1350 kW
Voltage	: 900 Volts
Rotational speed	: 750 rpm



Electric Propulsion Motors

Number	:	3
Manufacturer	:	Canadian Westinghouse Co. Ltd.
Power	:	3675 kW = 5000 SHP
Voltage	:	900 Volts
Rotational speed	:	136 rpm (icebreaking) to 170 rpm (free running)

Propellers

Type	:	Fixed pitch
Number	:	1 centre, 2 wing
Diameters	:	4.1 metres
No. of blades	:	4
Developed area	:	7.2 m ² (centre) 6.8 m ² (wing)
Max. pitch	:	3.3 metres (centre) 3.2 metres (wing)

Auxiliary Diesel Generators

Number	:	3 generator sets
Manufacturer	:	Canadian Fairbanks-Morse Co. Ltd.
Engine type	:	38D8-1/8
Number of cylinders	:	5
Power	:	588 kW = 800 BHP
Rotational speed	:	720 rpm
Generator type	:	Marine TGZJM
Generator power	:	700 kW
Voltage	:	450 Volts, 60 Hz

Drawings of the ship are shown in the following figures. Figure A.1 shows the elevation plan of "JOHN A. MACDONALD". The machinery arrangement is given in Figure A.2.



A.4

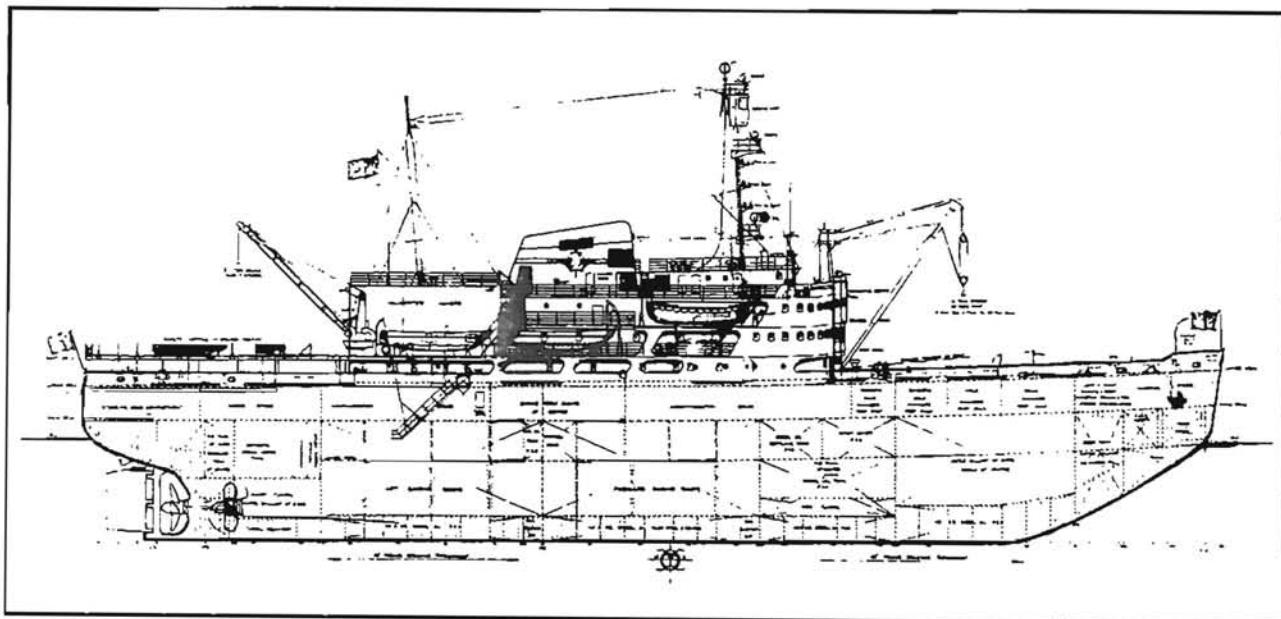


Figure A.1.
Elevation plan of "JOHN A. MACDONALD".

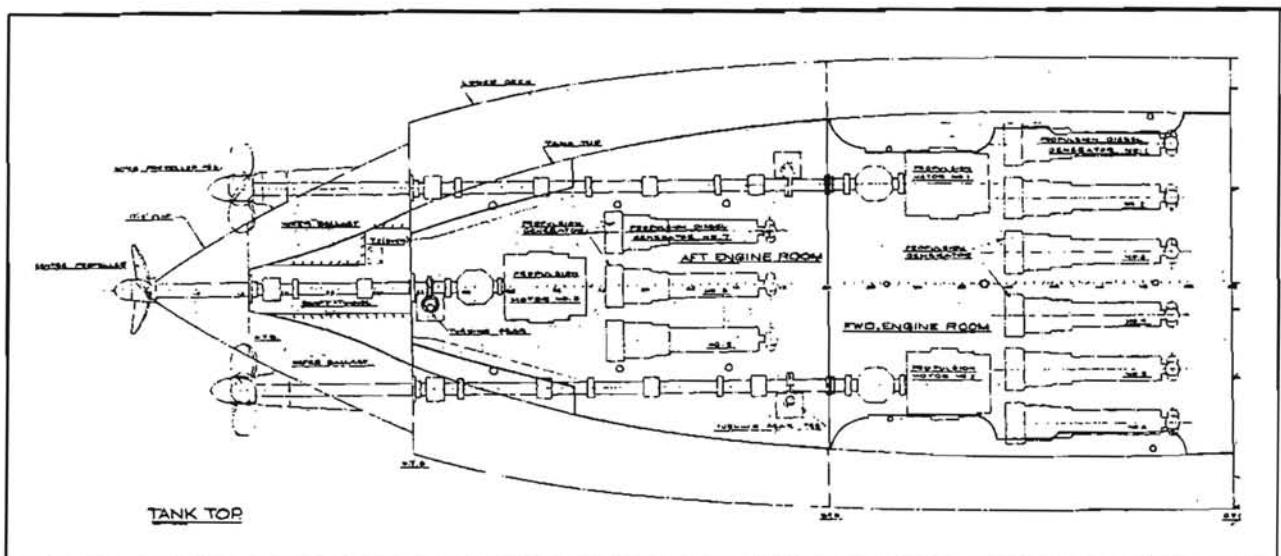


Figure A.2.
Machinery arrangement for "JOHN A. MACDONALD".

Vibration measurements have been performed on the main and auxiliary engines of the ship in order to determine the generated frequency components. The vibrations were measured on the steel foundation of the engines during normal sailing conditions. The measured velocity levels are shown in Figures No. A.3. and No. A.4.

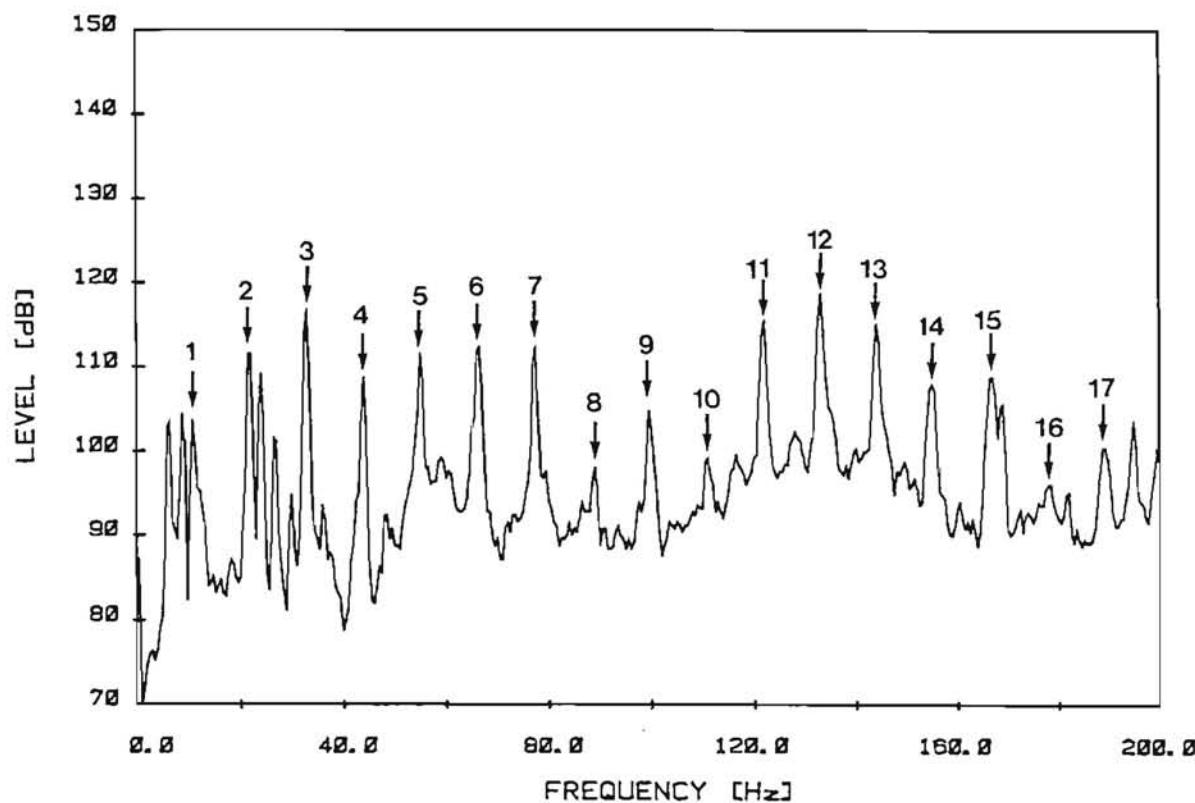


Figure A.3.

Velocity level (dB re. 10^{-9} m/s) measured on the foundation for main engine No. 9. Nominal rotational speed 700 rpm.

From Figure A.3 it can be seen that the spectra of the measured velocity level for a main engine consists of a number of discrete frequency components. The spacing between the discrete frequency components is 11.1 Hz corresponding to a revolutional speed of 668 rpm. The maximum velocity level is approximately 120 dB re. 10^{-9} m/s.

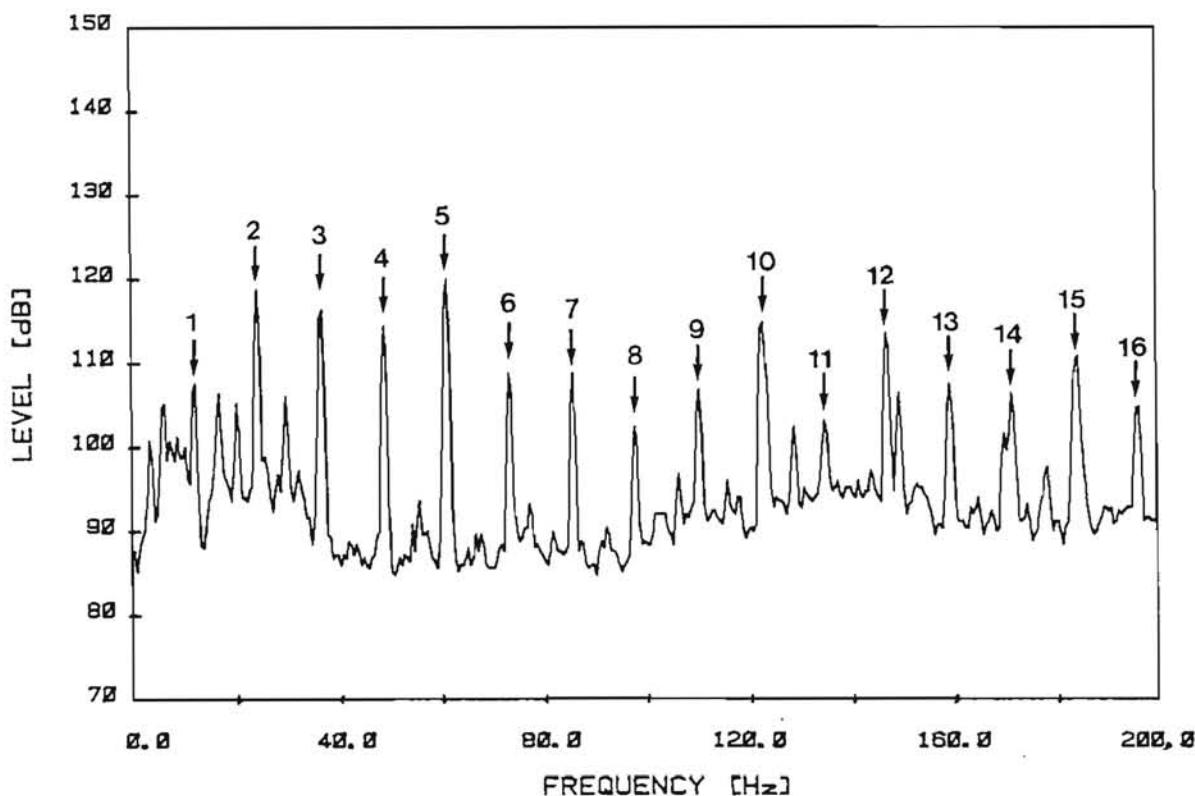


Figure A.4.
Velocity level (dB re. 10^{-9} m/s) measured on the foundation of auxiliary engine No. 3. Nominal rotational speed 720 rpm.

The frequency spectra for an auxiliary diesel generator, given in Figure A.4, is also dominated by discrete frequency components. The spacing between the components is 12.3 Hz corresponding to a revolutionary speed of 738 rpm. The maximum level is approximately 120 dB re. 10^{-9} m/s.

In order to illustrate the frequency components generated by the propeller, Figure A.5 shows the velocity level measured on the shell plating close to the centre propeller.

It can be seen from Figure A.5 that also the propeller generates discrete frequency components. The blade pass frequency of the propeller is dominant at approx. 5.5 Hz corresponding to four times the revolutionary speed of the shaft, 80 rpm or 1.3 Hz.

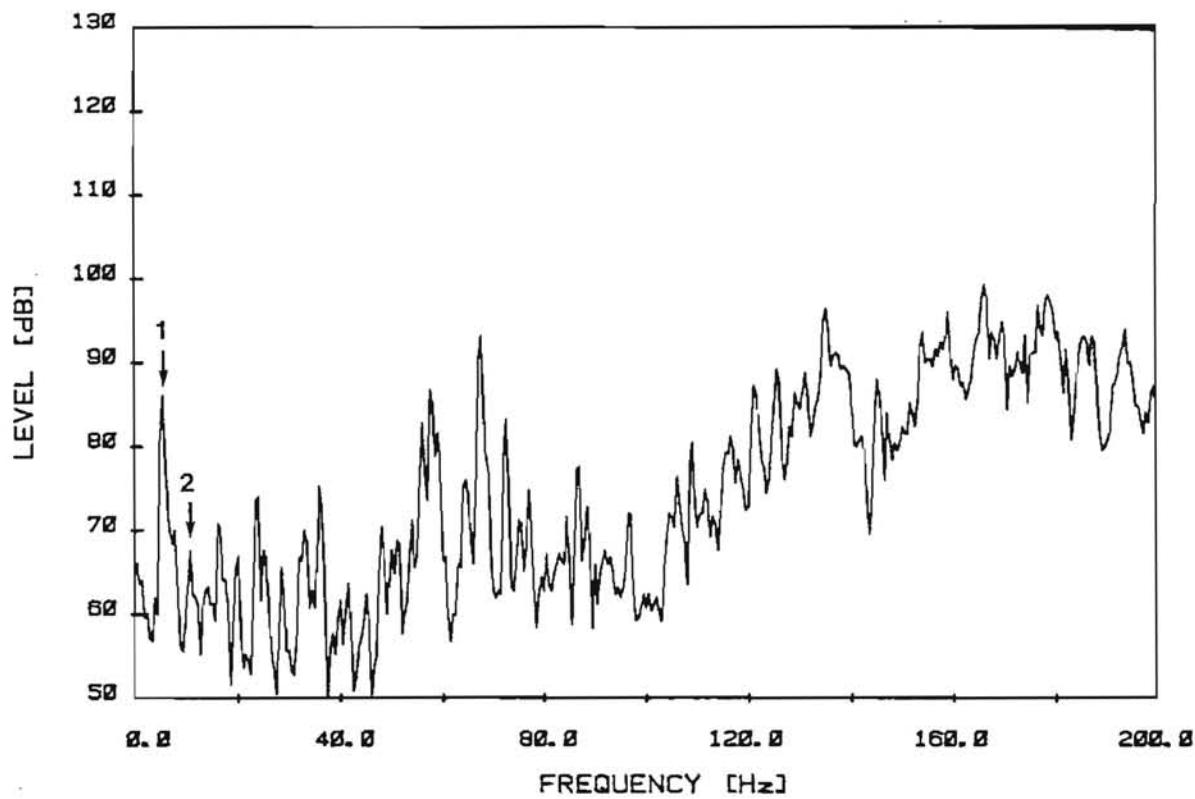


Figure A.5.

Velocity level (dB re. 10^{-9} m/s) measured on the shell plating in the aft end of the shaft tunnel for the centre propeller. Revolutionary speed 80 rpm for centre propeller.

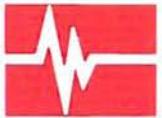
The discrete frequencies at 60-80 Hz are probably generated by other sources e.g. the main engines. At frequencies above 100 Hz the cavitation noise from the propellers can be seen as a more broad band noise excitation of the shell plating.

It must be emphasized that the vibration spectra given above are only examples meant to illustrate the frequency components generated by the engines and propeller. The frequencies will change with the revolutionary speed and the magnitude with the load. Furthermore, the vibration level will be very dependent on the type of structure where the measuring position is placed.



APPENDIX B

Geographic Locations and Environmental Data



B.1 Route

The underwater noise recordings were carried out during a voyage with the icebreaker "JOHN A. MACDONALD" from Halifax, Nova Scotia, to the Nanisivik Mine on the northern Baffin Island. The route was from Halifax, along the west coast of Greenland, through Lancaster Sound and Admiralty Inlet to the Nanisivik Mine in Strathcona Sound.

During this voyage three underwater noise measurements were performed. The locations where the recordings were performed are shown in Figure B.1. A detailed description of each location is given in the following.

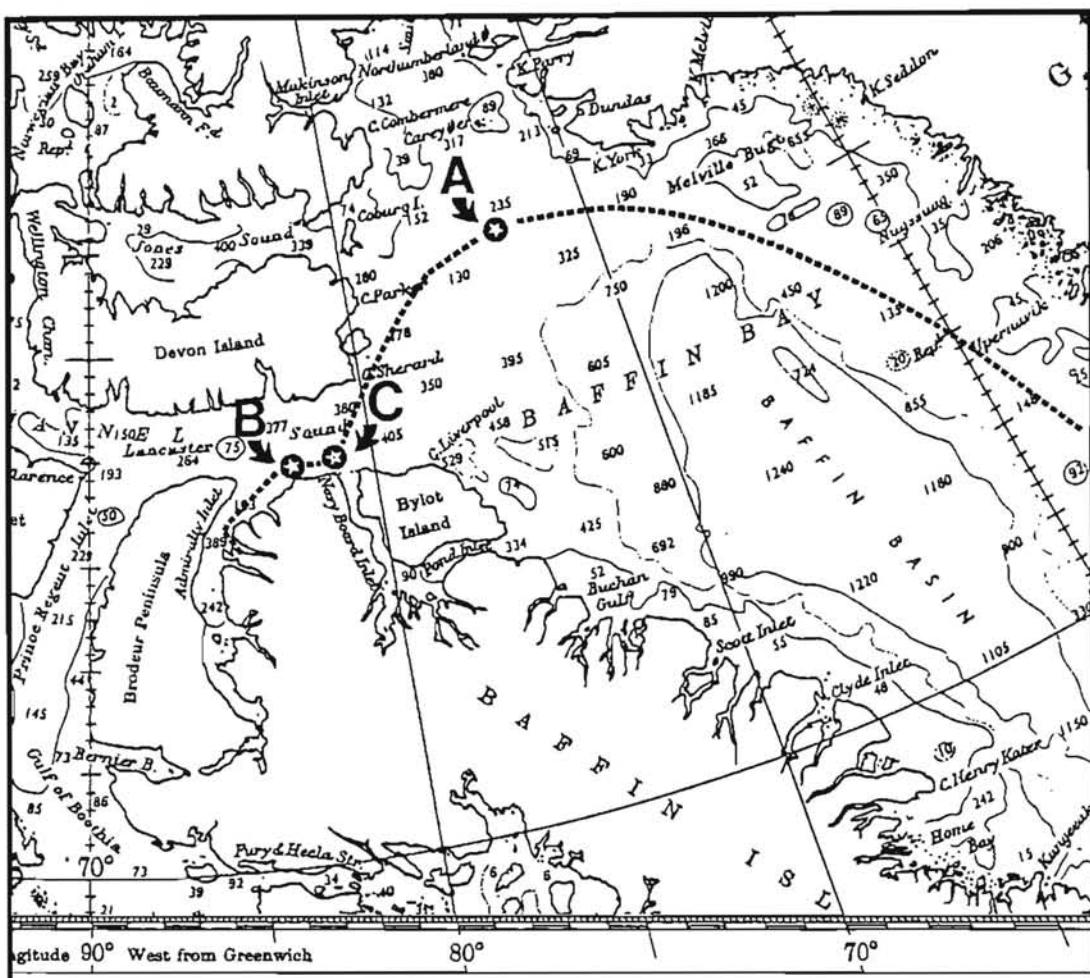


Figure B.1.
Final part of the "JOHN A. MACDONALD" route and measuring locations A, B and C.



B.2 Geographic Locations

The first measurement was carried out on the 25th June in the northern part of Baffin Bay between Thule (Greenland) and Devon Island (Canada). This location is referred to as "Location A".

The measurements at Location A were performed from a fixed measuring site with the icebreaker moving. The ship started approaching from 35 km away, passed the measuring site at a distance of approx. 700 metres and continued out to a distance of approx. 6.8 km. Then it turned around and approached the measuring site again. The route is illustrated in Figure B.2.

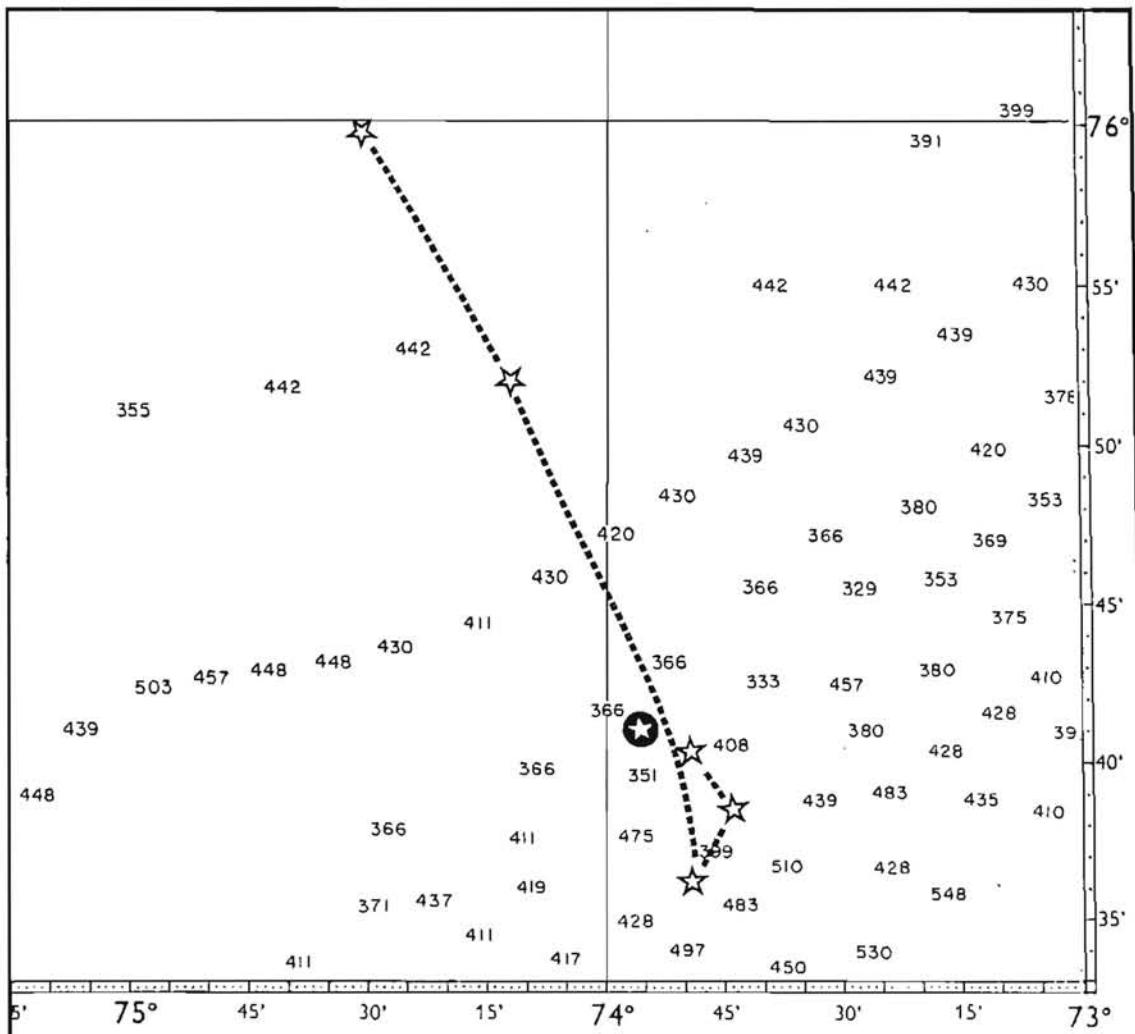


Figure B.2.

Route sailed by the icebreaker on the 25th June at measuring Location A in Baffin Bay.

★ : Measurement site

☆ : Shot tests.



At the measurement site, the "Danish" and the "Canadian" study teams were spaced approximately 1 km. All distances given in this report refer to measurement site No. 1 with the "Danish" team. The position of the site was approximately $75^{\circ} 41'3\text{ N}$ and $73^{\circ} 53'2\text{ W}$.

The icebreaker was stopped five times to perform sound transmission loss measurements. The distances from the measuring site to the ship were 35000, 17800, 7770, 1700 and 675 metres. The locations are marked with stars in Figure B.2.

The second measurement was carried out on the 27th June in the eastern part of Lancaster Sound. This location is referred to as "Location B". The procedure for the underwater noise measurements was changed at this location due to very slow progress of the icebreaker. It was necessary to move the measuring team in order to obtain different distances to the ship. With the icebreaker operating at a constant position, the measuring party was first flown out to a distance of approximately 35 km from the ship. When the recordings at this distance were finished, the team was moved again to four other distances. The locations of the measurement sites and the icebreaker during the second measurement are shown in Figure B.3.

The distance to the ship and the position for the five measurement sites used at Location B are given in Table B.1.

Distance	Position			

35200 metres	73°	50.0'N	81°	55.0'W
14470 metres	73°	49.3'N	82°	00.9'W
6860 metres	73°	49.1'N	82°	04.4'W
1880 metres	73°	48,8'N	82°	07.9'W
1170 metres	73°	48.5'N	82°	10.0'W

Table B.1.
Distance to ship and position of the measurement sites
used on the 27th June at Location B.

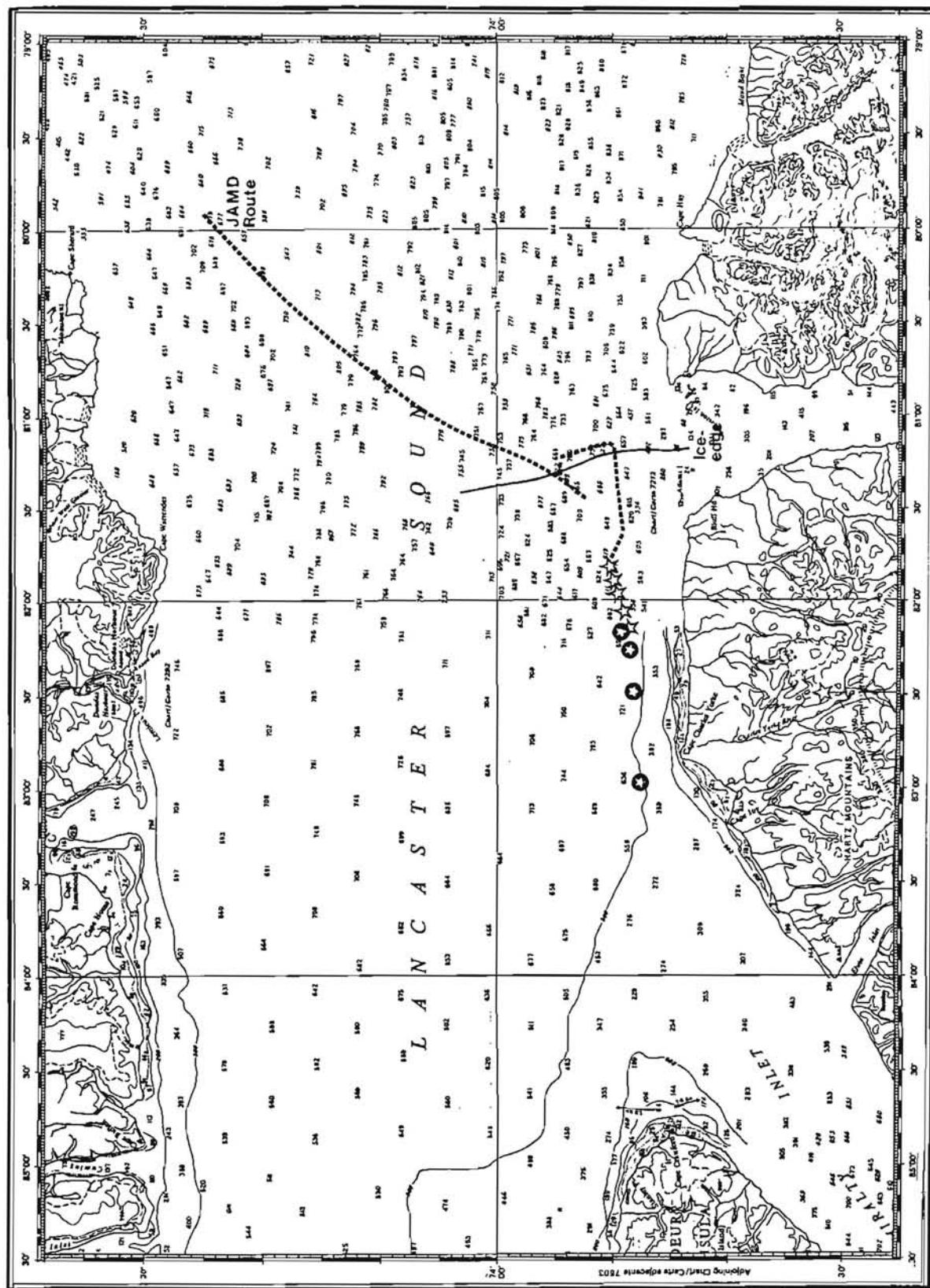


Figure B.3.
Location of measurement sites during the measurements performed on the 27th June at Location B.
●: Measurement site ★: Position of icebreaker



B.6

During all measurements on the 27th June, with the exception of the last one, the "Danish" and the "Canadian" team performed their measurements from the same measurement site. At the last measurement when the distance to the ship was 1170 metres, the two teams were spaced approximately 200 metres.

The third series of measurements was carried out on the 1st July at the ice-edge in the eastern entrance of Lancaster Sound . This location is referred to as "Location C". The measurements were performed from a single site and no variation in the distance to the icebreaker was achieved. During the measurements the ice-breaker was still breaking very heavy ice and was making little progress. The distance from the icebreaker to the ice-edge was approximately 55 km. The positions of the measurement site and the icebreaker were $73^{\circ}47'N$, $81^{\circ}14'W$ and $73^{\circ}46'N$, $82^{\circ}53'W$, respectively. The locations is shown in Figure B.4.

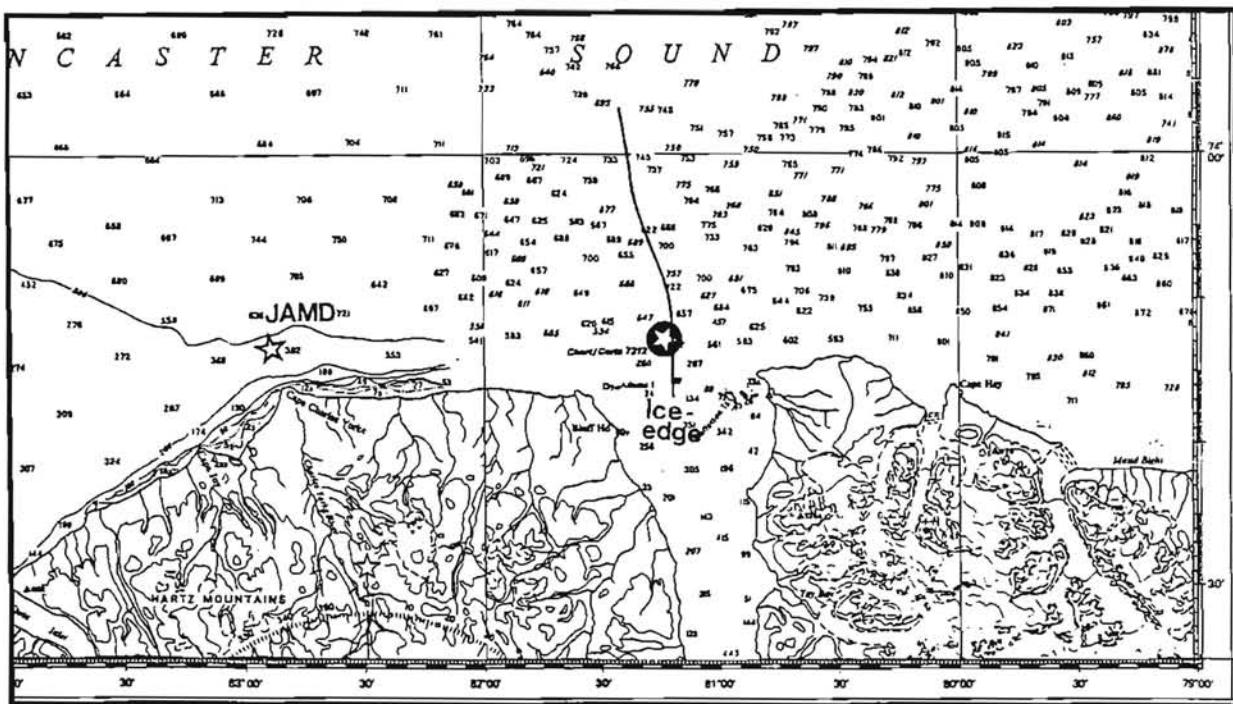


Figure B.4.
Location of measurement site C and position of the icebreaker.



B.7

B.3 Description of the Measurement Locations

Location A was placed in a pack ice area with large floes and open water. The ice concentration varied from 5/10 to 8/10. In general the ice thickness was less than 1 metre. An ice chart drawn by the ice observer from the icebreaker is shown in Figure B.5.

A photograph taken from the helicopter on the flight to Location A is shown in Figure B.6 as an illustration of the ice conditions.

The weather during the measurements was calm with light winds and periods of fog. The air temperature was 0-5°C below zero.

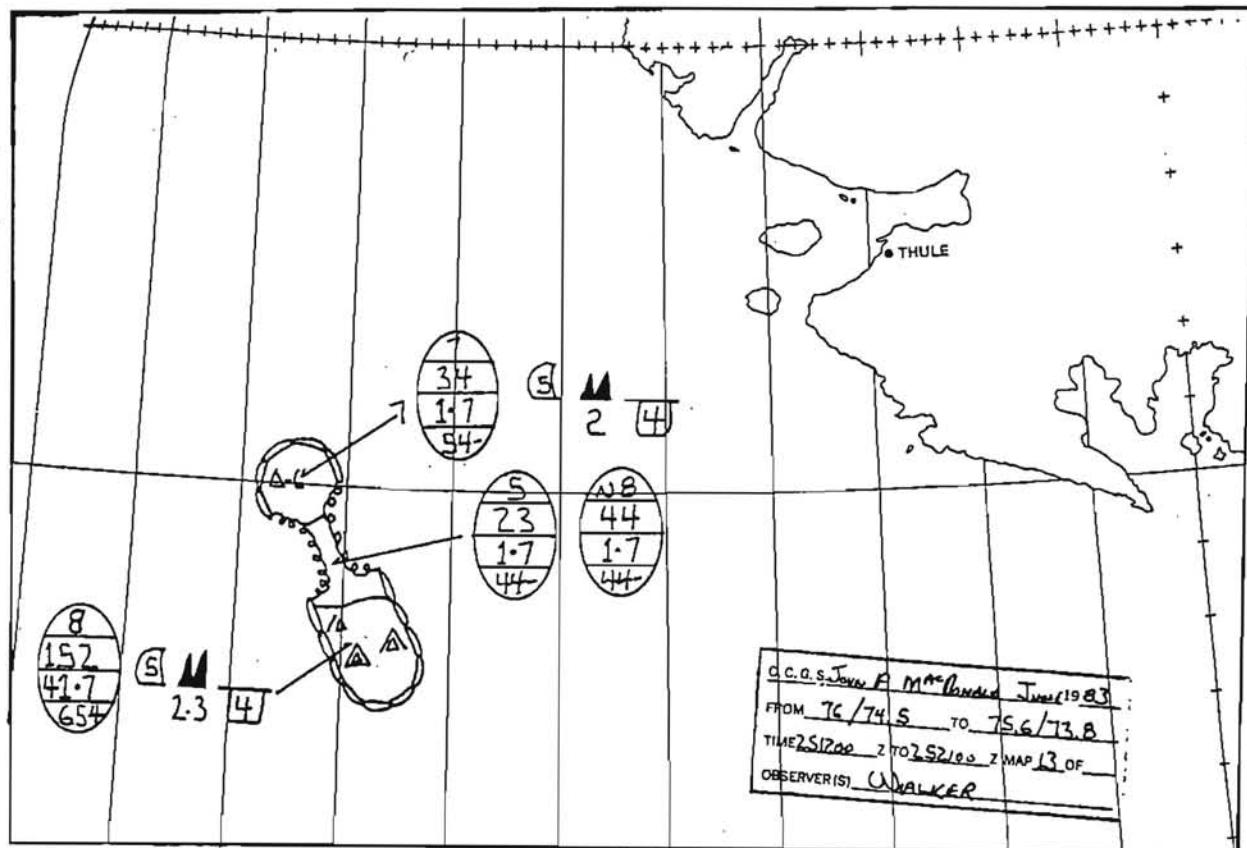


Figure B.5.
Ice chart of the area around Location A.



Figure B.6.
Aerial photograph of Location A.

Location B was placed in an area with 10/10 first year fast ice and few hummocks. The ice thickness was approximately 2.5 metres. Large areas of the ice were covered with melted fresh water. The ice chart of the area is shown in Figure B.7. A photograph taken from the helicopter is shown in Figure B.8.

During the measurements the weather was very calm with no wind and a high temperature in the sun. At the end of the measurements, the wind increased and the temperature dropped.

At Location C the measurement site was placed at the ice edge between the fast ice cover in Lancaster Sound and the open water north of Bylot Island. No drifting ice could be seen from the ice edge. The ice chart of the area is shown in Figure B.7 and a photograph is given in Figure B.9.

The weather during the measurements was cloudy with moderate westerly winds.



B.9

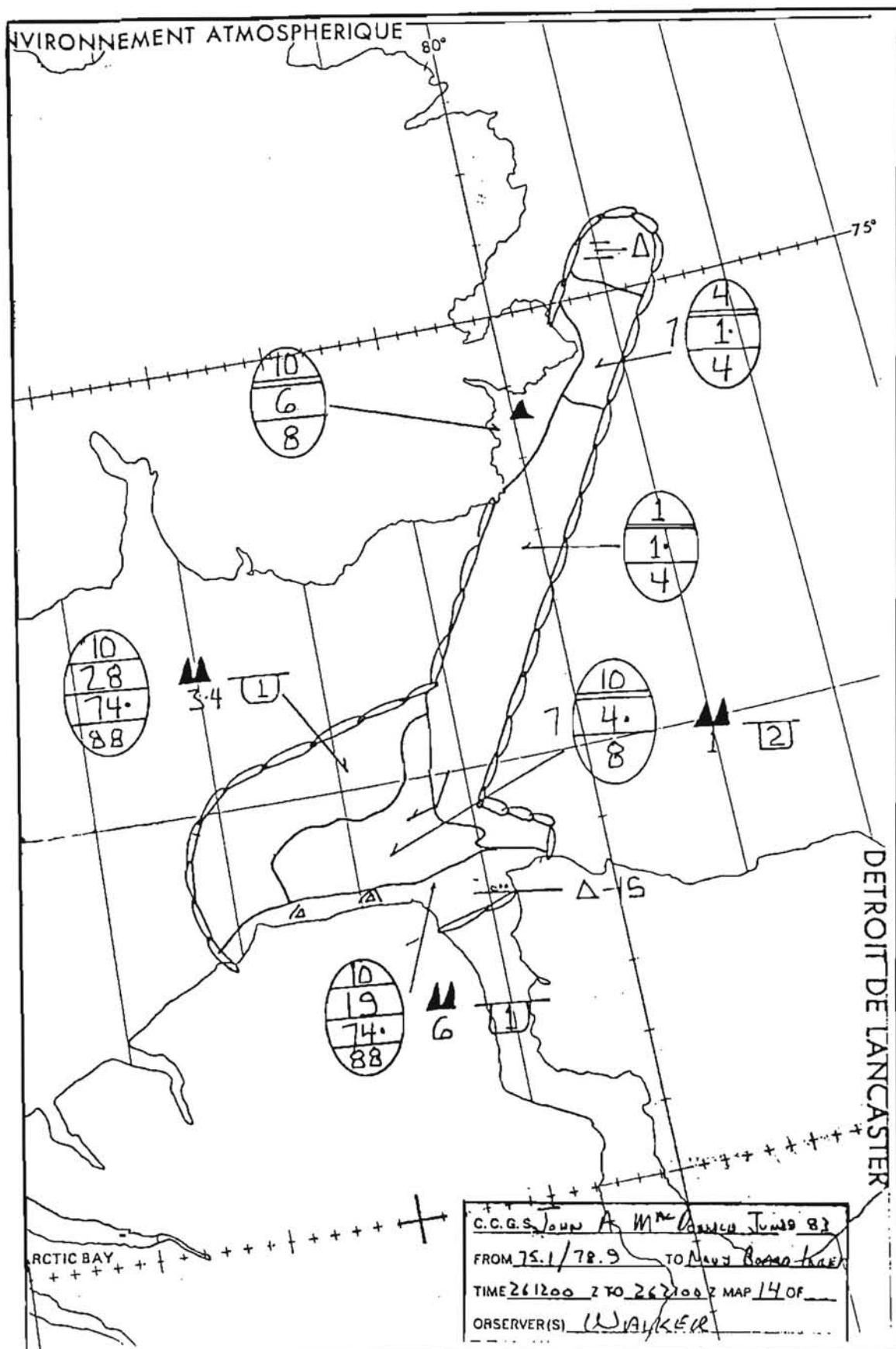


Figure B.7.
Ice chart from the area around Locations B and C.



B.10

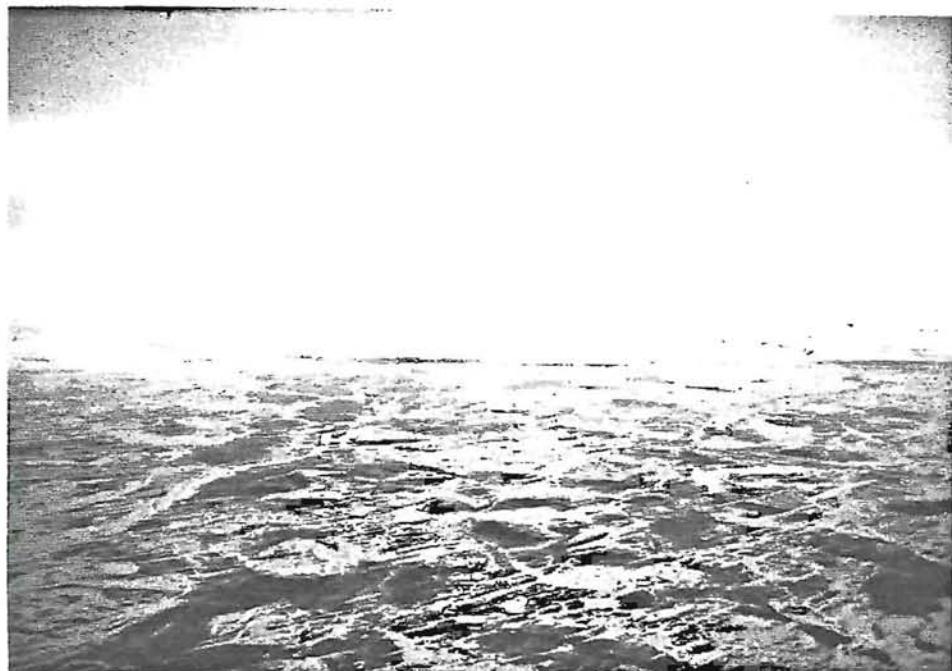


Figure B.8.
Aerial photograph of Location B.



Figure B.9.
Aerial photograph of Location C.



B.4 Hydrographic Data

At Locations A and B, measurements of the water temperature and salinity were conducted. The measurements were carried out with equipment of the type "Electronic Swichgear" to a depth of 100 metres.

The results of the temperature and salinity measurements together with the calculated sound velocity are given in Figure B.10 for Location A and in Figure B.11 for Location B.

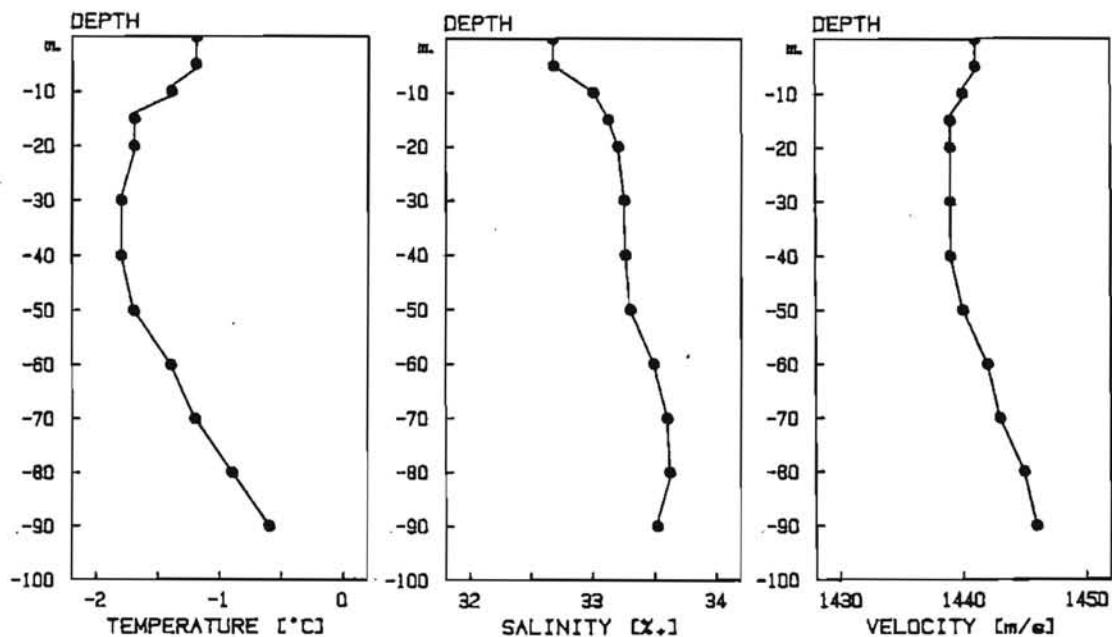


Figure B.10.
Measured temperature and salinity profiles from Baffin Bay, Location A, performed in the same period as the noise measurements. The velocity profile has been calculated from the measured data.

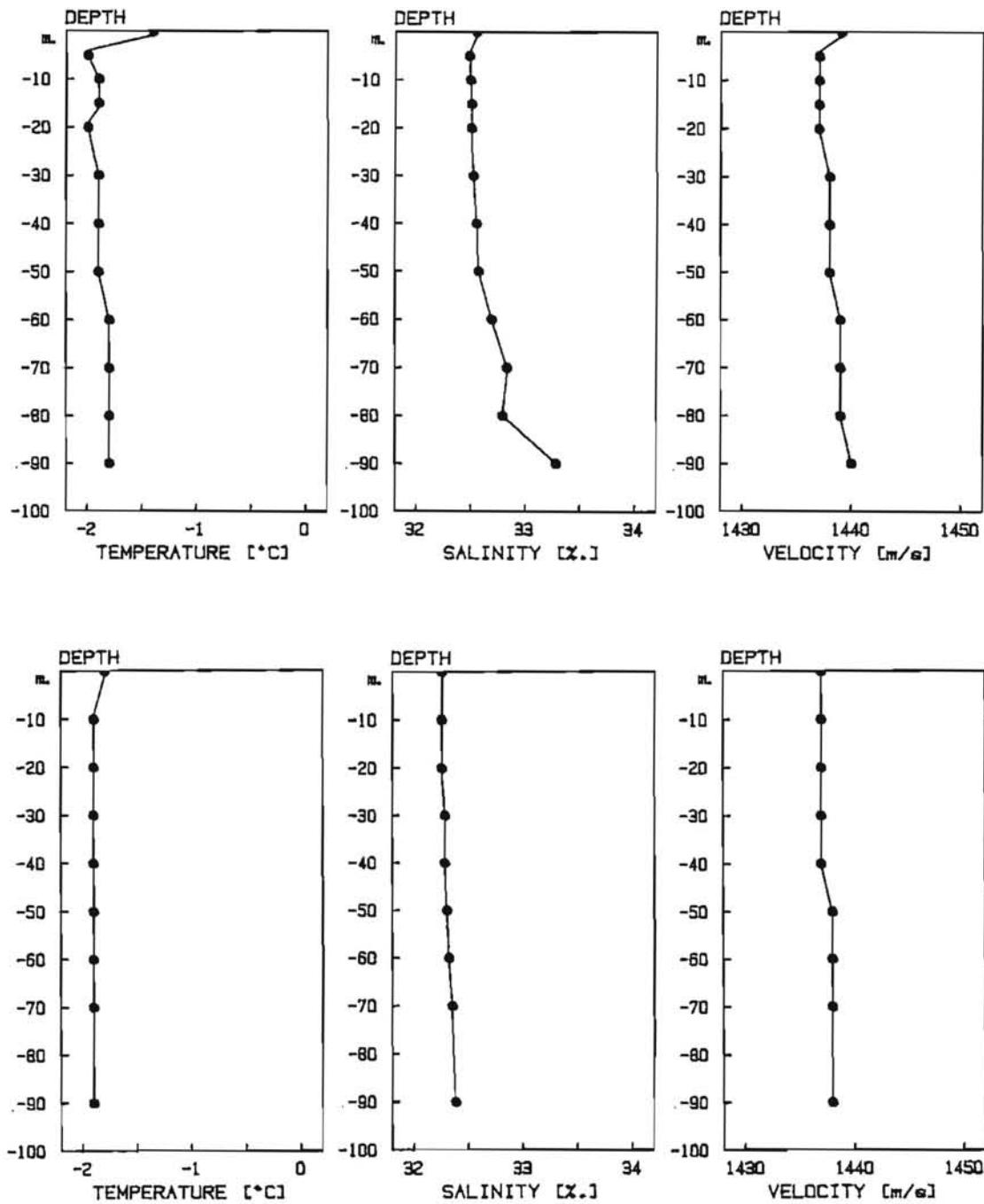


Figure B.11.
Measured temperature and salinity profiles from 2 tests in Lancaster Sound, Location B, performed in the same period as the noise measurements. The velocity profile has been calculated from the measured data.
Upper: Time 05.26 Lower: Time 21.17



The nominal underwater sound velocity for Locations A and B have been calculated, based on the measured temperature and salinity values. For depths below 100 m, data of other studies from Lancaster Sound and Baffin Bay have been applied. For Location A in Baffin Bay data obtained by Mellen and Browning, Ref. /16/ and Greenland Technical Organisation, Ref. /9/ have been applied. For Location B in Lancaster Sound data from Environmental Studies by Indian and Northern Affairs Canada, Ref. /15/ have been applied. The expected sound velocity profiles during the measurements are given in Figures B.12 and B.13.

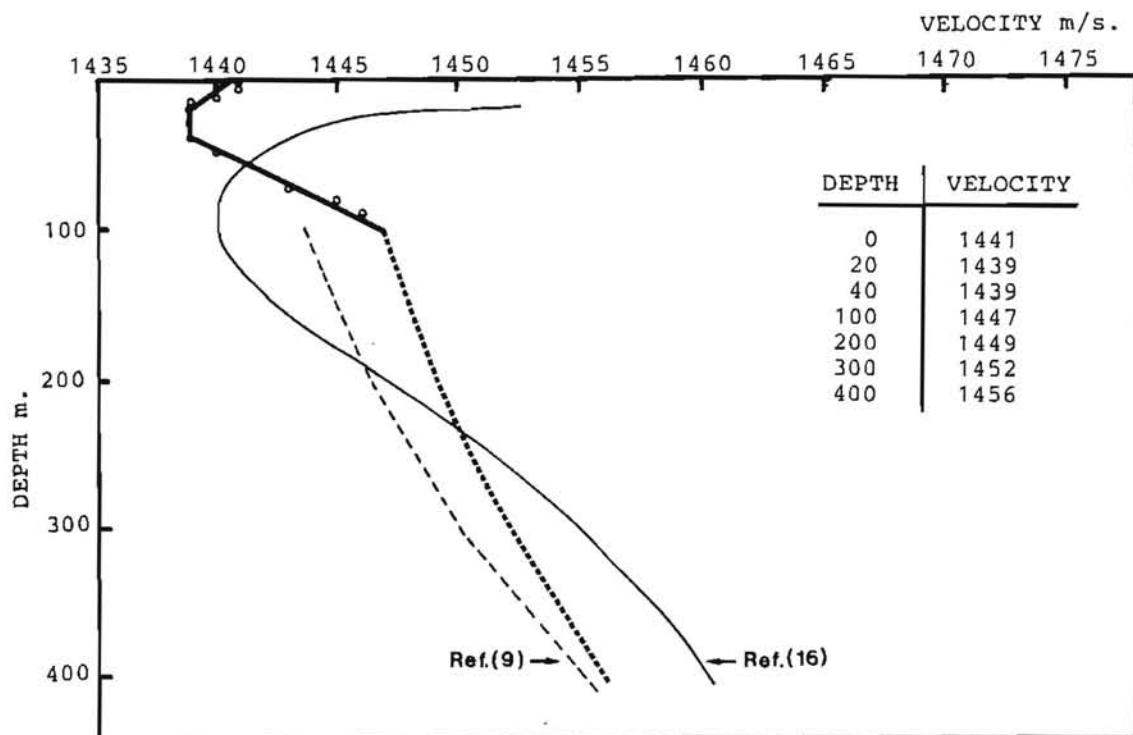


Figure B.12.
Calculated sound velocity profile from Location A in Baffin Bay.

The general positive gradient for the sound velocity with increasing depth which can be seen for both velocity profiles, indicate that upward refraction of the sound waves will occur. This means that the energy is concentrated in the upper layers of the water.

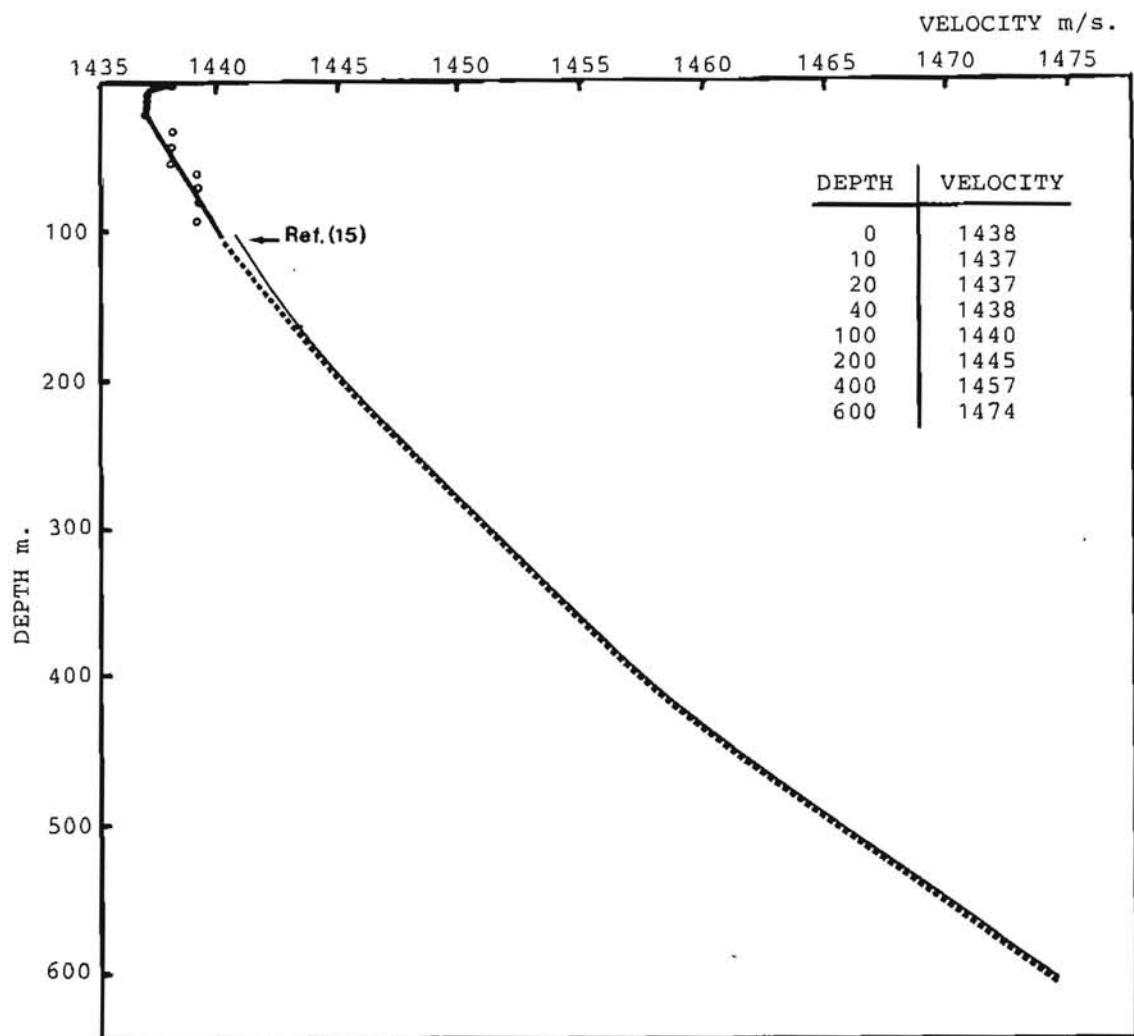


Figure B.13.
Calculated sound velocity profile from Location B in
Lancaster Sound.

This is illustrated in Figures B.14 and B.15 which show the ray diagrams of the sound field calculated with a ray-tracing computer programme. The ray-trace diagrams have been calculated based on the measured sound velocity profile from Locations A and B and a source depth of 4 metres.

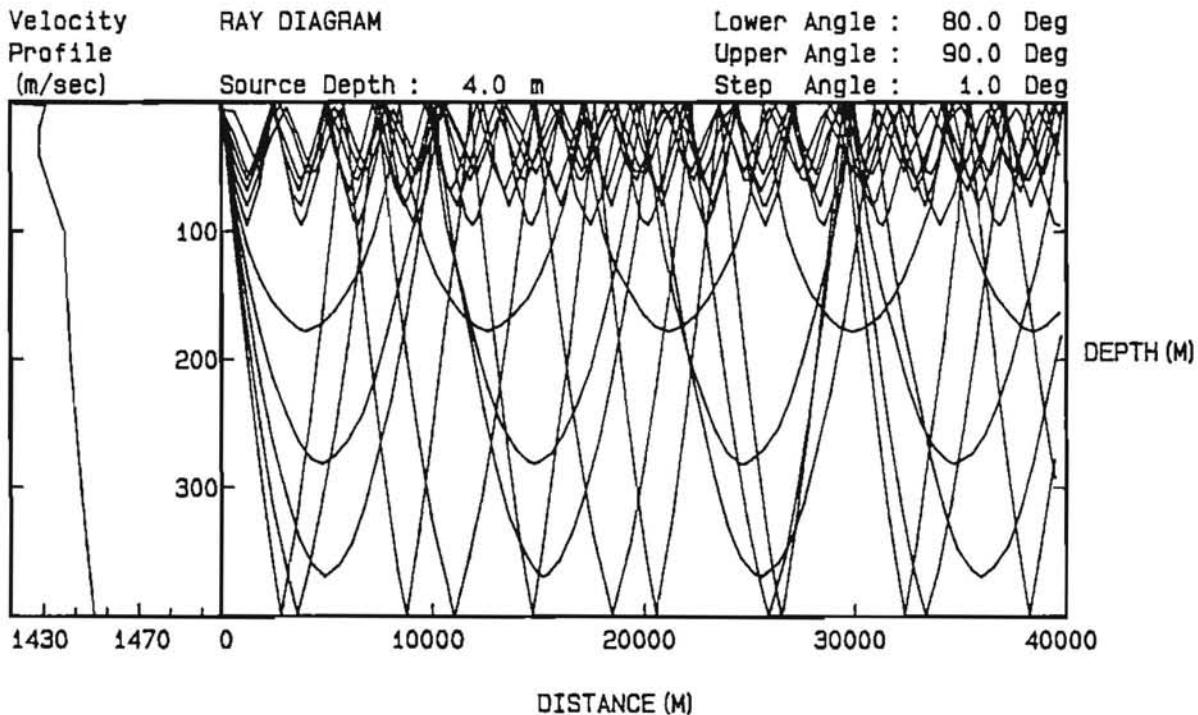


Figure B.14.
Ray-trace diagram of the sound field corresponding to the conditions in Baffin Bay at Location A. Source depth: 4 metres.

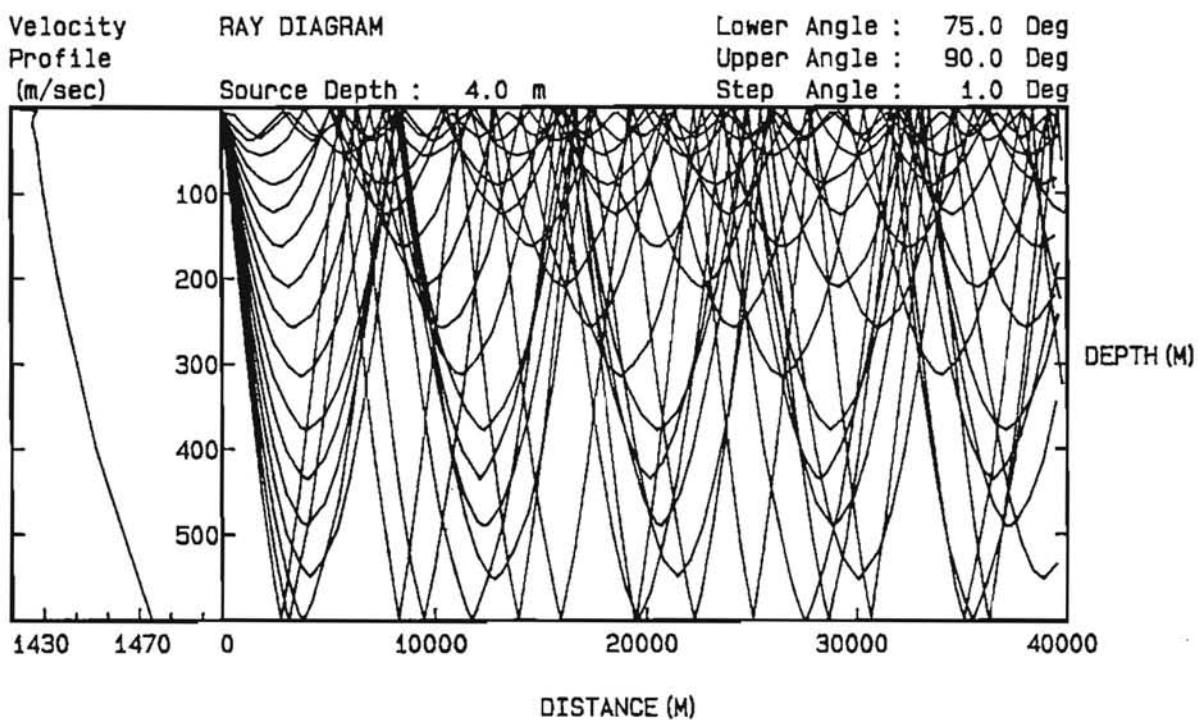


Figure B.15.
Ray-trace diagram of the sound field corresponding to the conditions in Lancaster Sound at Location B. Source depth: 4 metres.



APPENDIX C

Results from Ambient Noise Measurements

CONTENTS

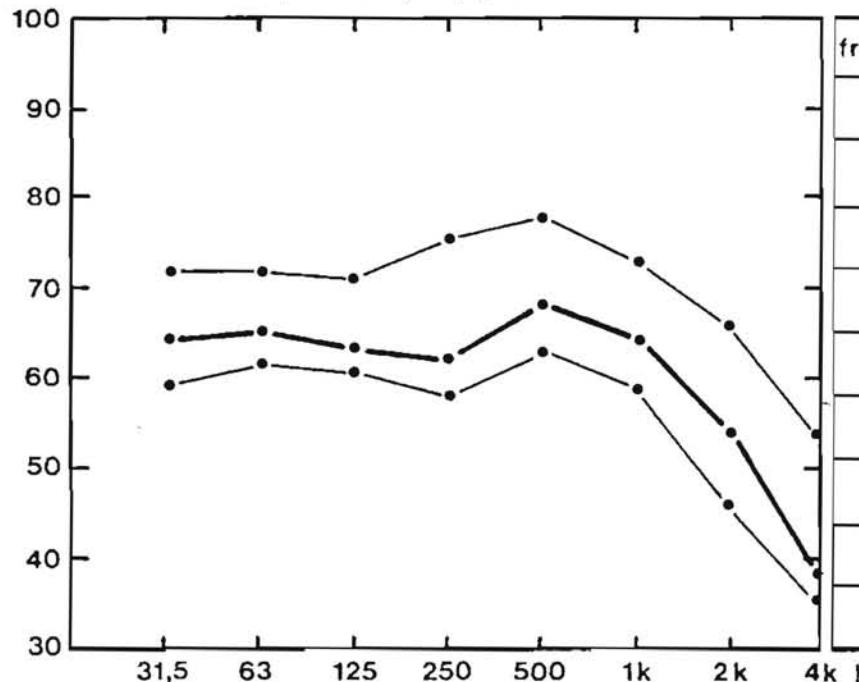
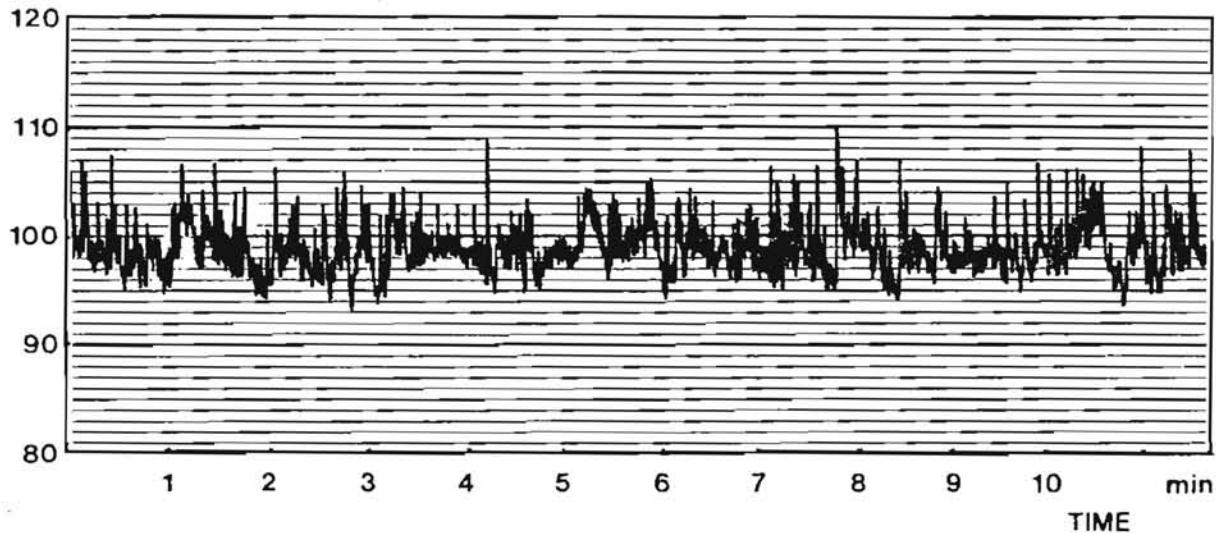
	<u>Page</u>
No. 1, Baffin Bay, Location A, Hydrophone depth 50 m :	C.3
No. 2, Lancaster Sound, Location B, Hydrophone depth 50 m :	C.4
No. 2A, Lancaster Sound, Location B, Hydrophone depth 5 m :	C.5
No. 2B, Lancaster Sound, Location B, Hydrophone depth 50 m :	C.6
No. 3, Ice-edge, Location C, Hydrophone depth 9 m :	C.7
No. 4, Ice-edge, Location C, Hydrophone depth 9 m :	C.8
No. 5, Ice-edge, Location C, Hydrophone depth 9 m :	C.9
No. 6, Ice-edge, Location C, Hydrophone depth 9 m :	C.10
No. 7, Ice-edge, Location C, Hydrophone depth 9 m :	C.11



C.3

Recording No. : 1
Date : 83.06.25
Measurement position: A

Time : 11.00
Water depth : 400 metres
Hydrophone depth : 50 metres

SPECTRUM LEVEL, dB re 1 μ Pa/ $\sqrt{\text{Hz}}$ OVERALL LEVEL, dB re 1 μ Pa

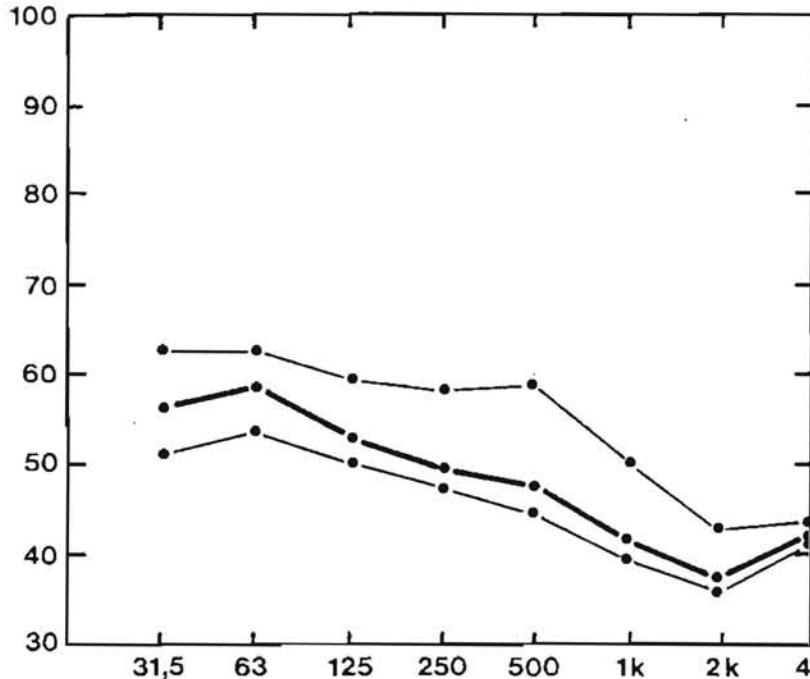
Remarks : Measured in Baffin Bay at position $75^{\circ} 42'N$ $73^{\circ} 52'W$ from a large floe (approx. 4 x 4 km). Area covered by pack ice and open water (see also Appendix B). The peak in the noise level above 250 Hz is due to a large amount of calls from bearded seals.



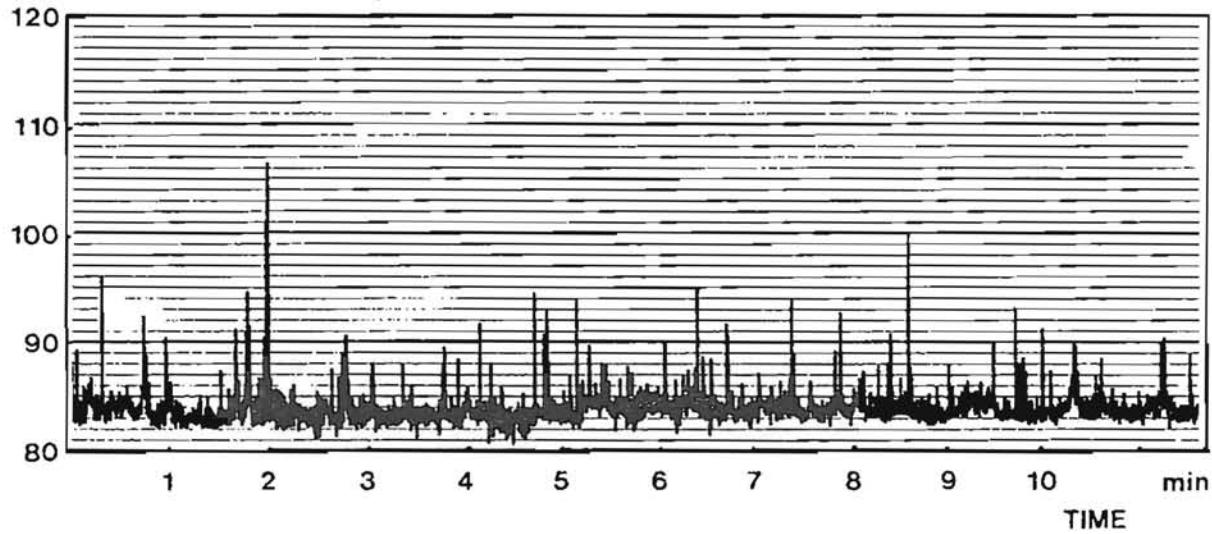
C.4

Recording No. : 2
Date : 83.06.27
Measurement position: B

Time : 06.55
Water depth : 600 metres
Hydrophone depth : 50 metres

SPECTRUM LEVEL, dB re $1 \mu\text{Pa}/\sqrt{\text{Hz}}$ 

frequency	L_1	L_{50}	L_{99}
Hz	dB	dB	dB
31.5	63	57	52
63.0	63	59	54
125	60	53	51
250	59	50	48
500	59	48	45
1000	51	42	39
2000	43	36	35
4000	44	42	42

OVERALL LEVEL, dB re $1 \mu\text{Pa}$ 

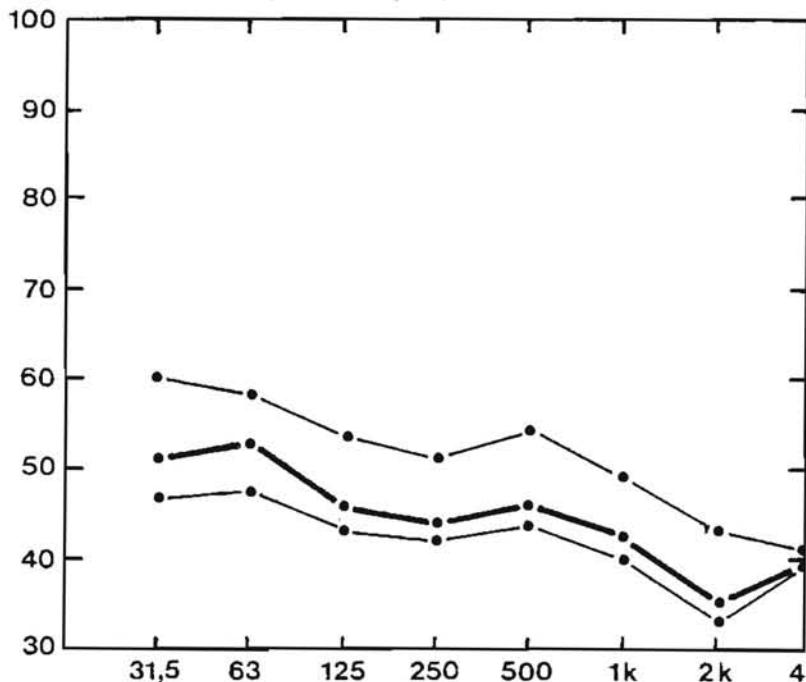
Remarks : Measured in Lancaster Sound from the fast ice with a thickness of 2.5 metres. Only very few biological sound can be heard (distant bearded seals).



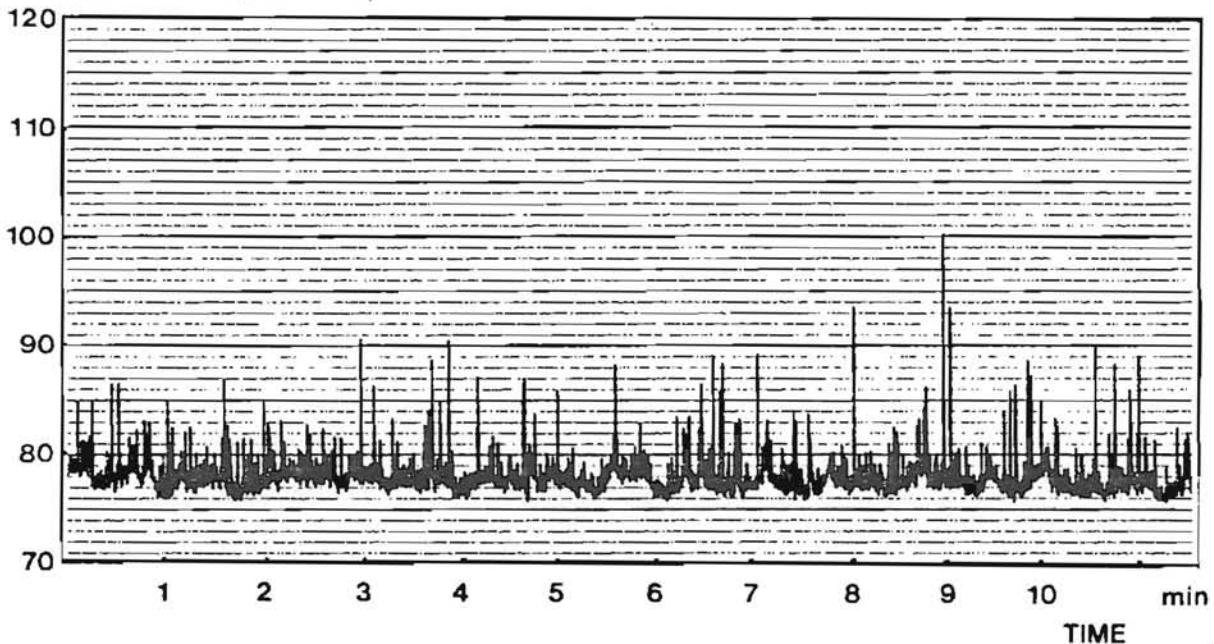
C.5

Recording No. : 2A
Date : 83.06.27
Measurement position: B

Time : 07.00
Water depth : 600 metres
Hydrophone depth : 5 metres

SPECTRUM LEVEL, dB re 1 μ Pa/ $\sqrt{\text{Hz}}$ 

frequency	L_1	L_{50}	L_{99}
Hz	dB	dB	dB
31.5	61	52	47
63.0	59	54	48
125	54	46	44
250	52	44	42
500	55	47	44
1000	50	43	40
2000	44	35	33
4000	41	39	39

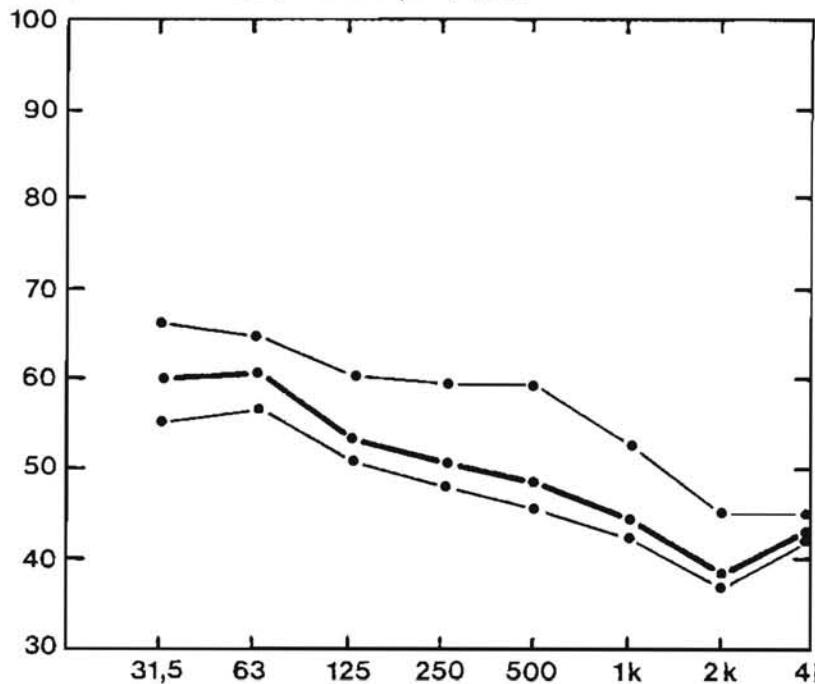
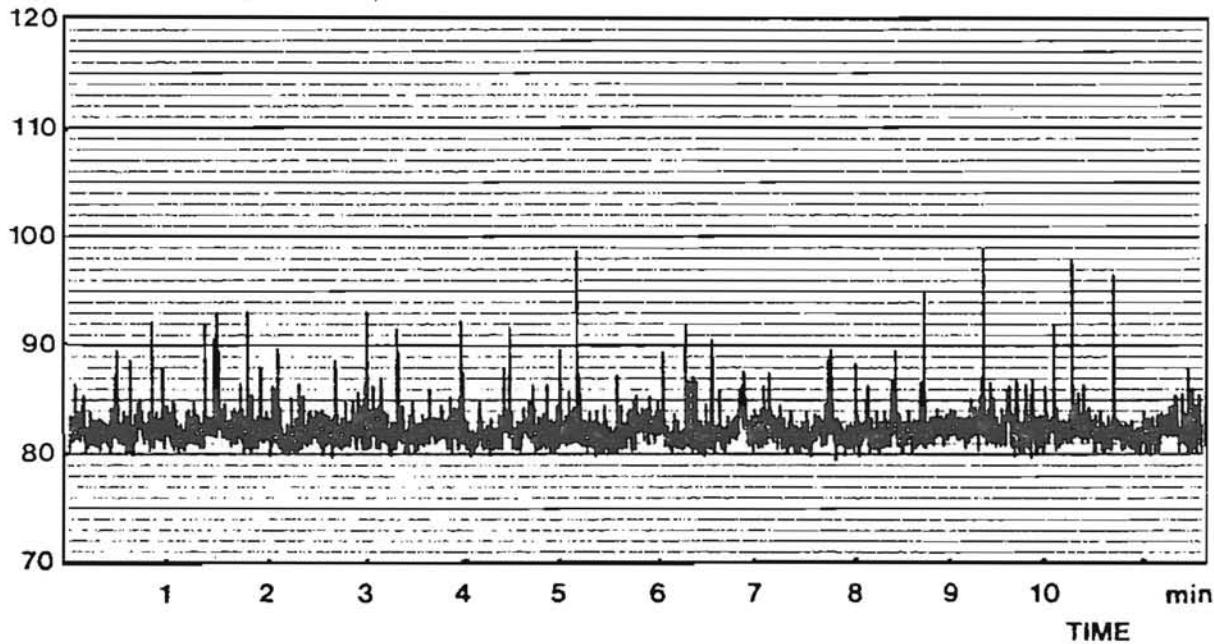
OVERALL LEVEL, dB re 1 μ Pa

Remarks : Measured parallel with recording 2B with a 4-channel tape recorder. Same position and conditions as for recording 2. Recording 2A and 2B are included in order to compare the ambient noise level measured at two different depths. It can be seen that the levels are approximately 6 dB lower for the shallow depth at low frequencies.



C.6

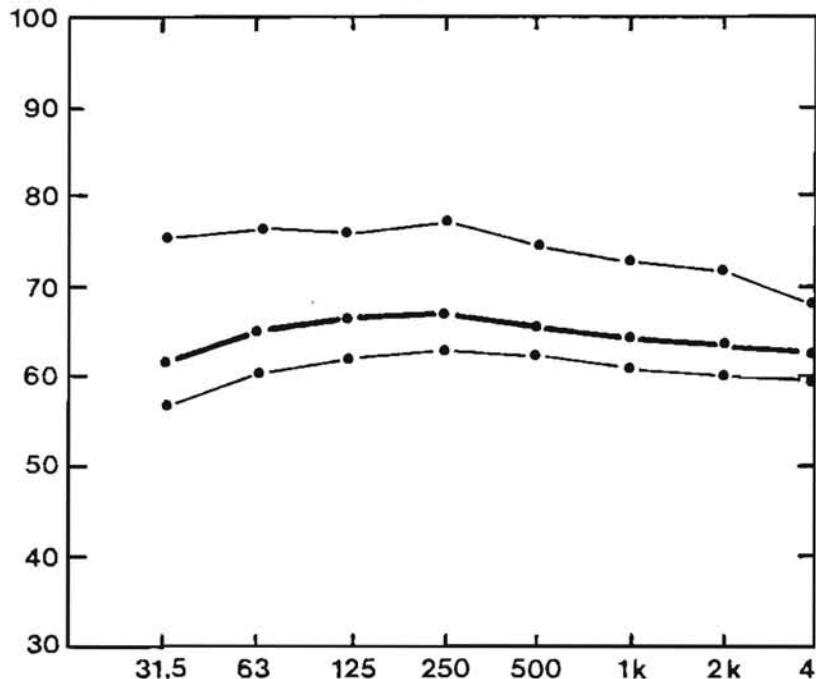
Recording No. : 2B Time : 07.00
Date : 83.06.27 Water depth : 600 metres
Measurement position: B Hydrophone depth : 50 metres

SPECTRUM LEVEL, dB re 1 μ Pa/ $\sqrt{\text{Hz}}$ OVERALL LEVEL, dB re 1 μ Pa

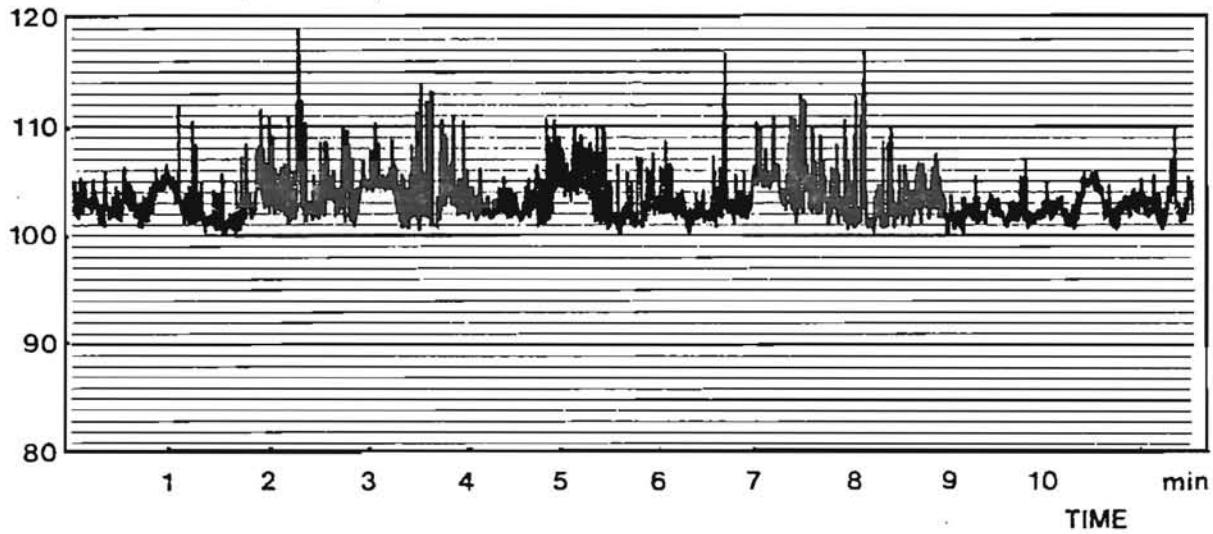
Remarks : Measured parallel with recording 2A with a 4-channel tape recorder. Same remarks as for recording 2A.



Recording No. : 3 Time : 12.47
Date : 83.07.01 Water depth : 500 metres
Measurement position: C Hydrophone depth : 9 metres

SPECTRUM LEVEL, dB re 1 μ Pa/ $\sqrt{\text{Hz}}$ 

frequency	L ₁	L ₅₀	L ₉₉
Hz	dB	dB	dB
31.5	76	62	57
63.0	77	65	61
125	76	67	62
250	78	67	63
500	75	66	63
1000	73	64	61
2000	72	64	60
4000	68	63	60

OVERALL LEVEL, dB re 1 μ Pa

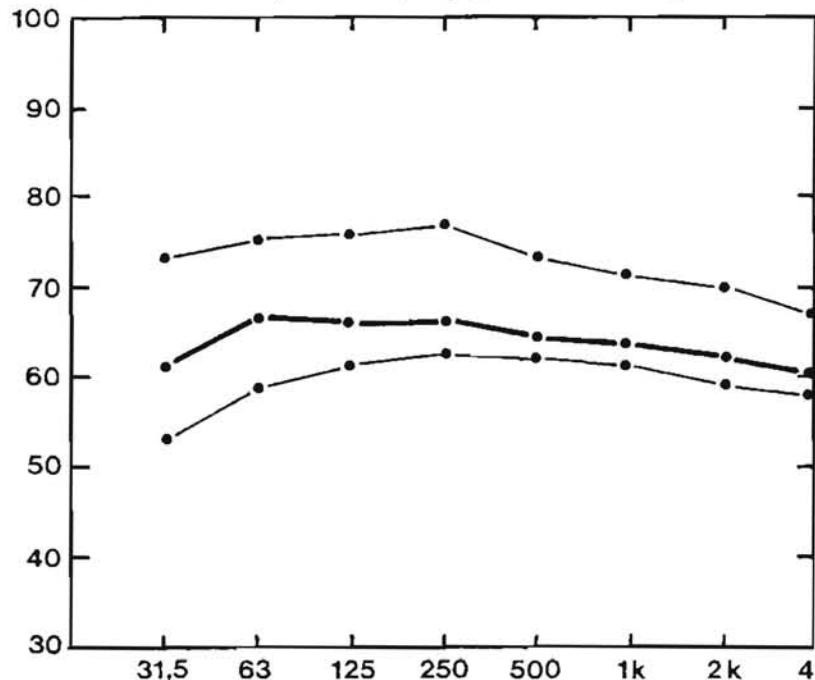
Remarks : Measured at the ice-edge in Lancaster Sound. The noise level is dominated by marine mammals. The icebreaker working 55 km away affects the noise level at low frequencies. The influence of the icebreaker can be seen in the overall level as fluctuations in the bottom level.



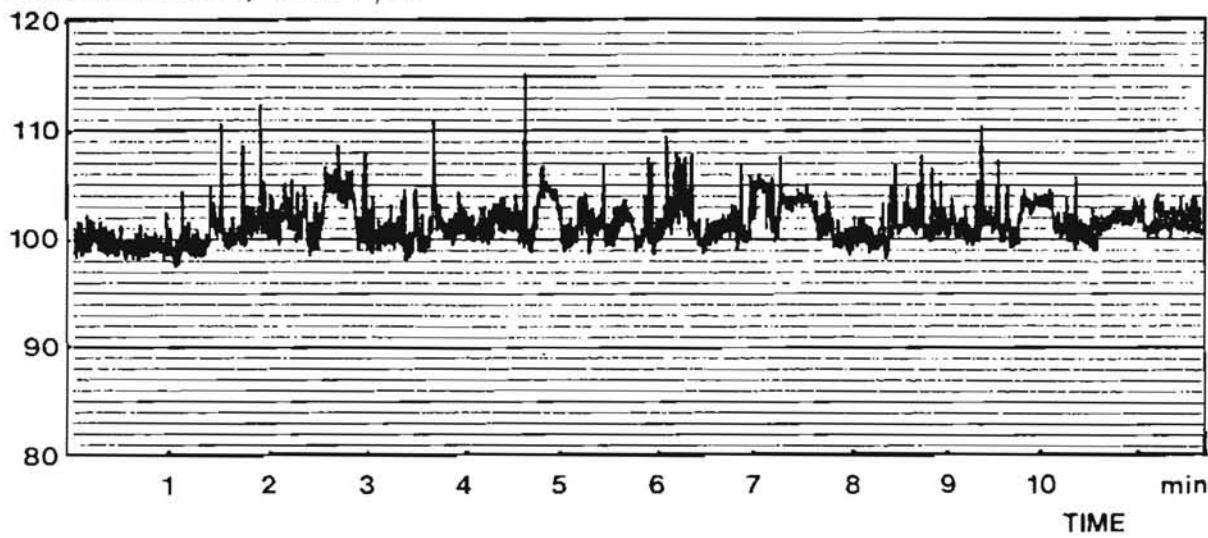
C.8

Recording No. : 4
Date : 83.07.01
Measurement position: C

Time : 13.14
Water depth : 500 metres
Hydrophone depth : 9 metres

SPECTRUM LEVEL, dB re 1 μ Pa/ $\sqrt{\text{Hz}}$ 

frequency	L_1	L_{50}	L_{99}
Hz	dB	dB	dB
31.5	74	61	53
63.0	76	67	59
125	76	66	62
250	77	66	63
500	74	65	62
1000	72	64	61
2000	70	62	59
4000	67	61	58

OVERALL LEVEL, dB re 1 μ Pa

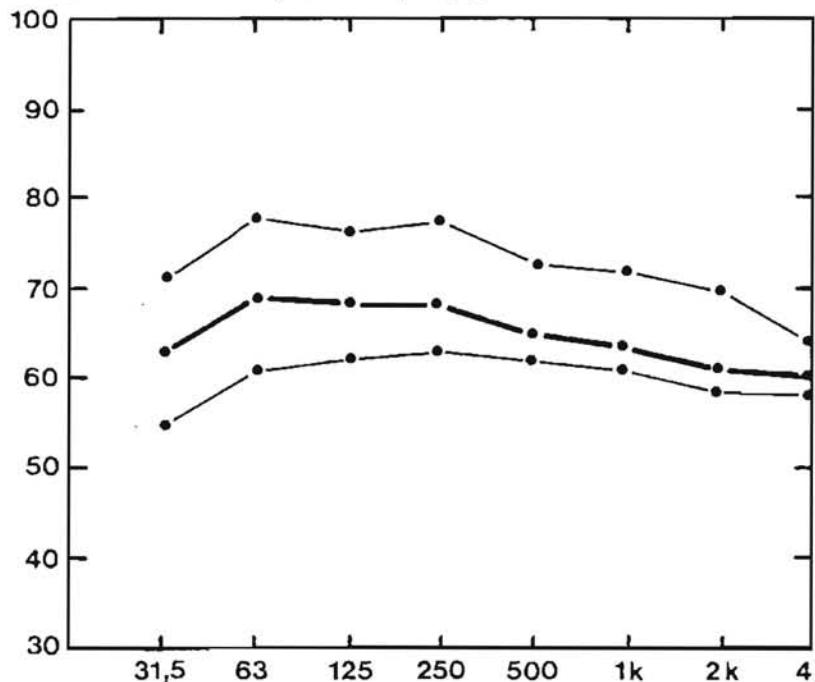
Remarks : Same remarks as for recording 3.



C.9

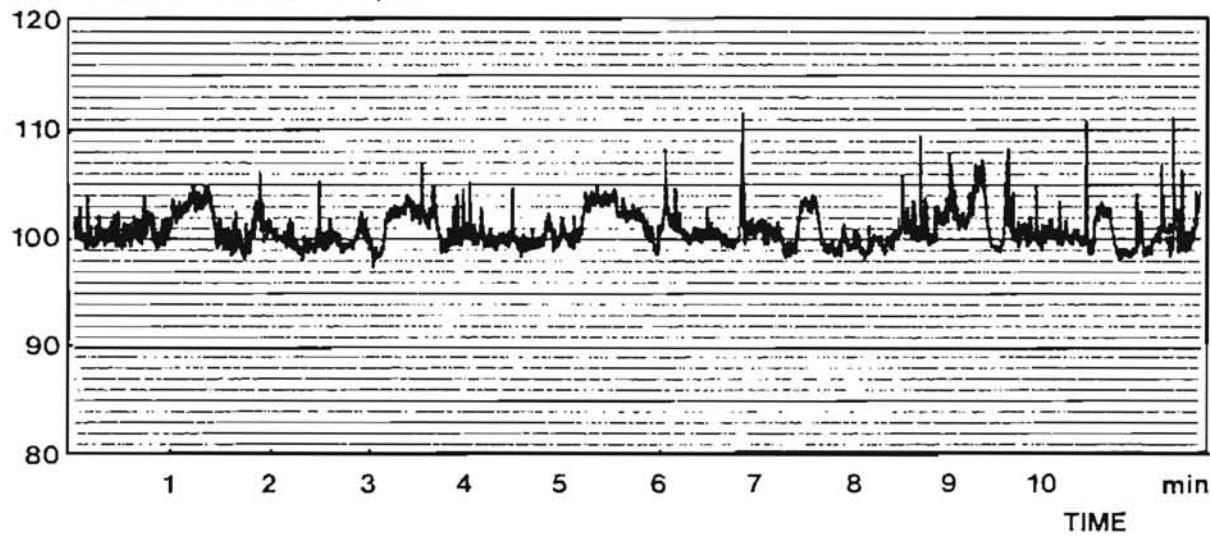
Recording No. : 5 Time : 14.00
Date : 83.07.01 Water depth : 500 metres
Measurement position: C Hydrophone depth : 9 metres

SPECTRUM LEVEL, dB re 1 μ Pa/ $\sqrt{\text{Hz}}$



frequency	L ₁	L ₅₀	L ₉₉
Hz	dB	dB	dB
31.5	72	63	55
63.0	78	69	61
125	77	69	63
250	78	69	63
500	73	65	62
1000	72	64	61
2000	70	61	59
4000	64	60	58

OVERALL LEVEL, dB re 1 μ Pa

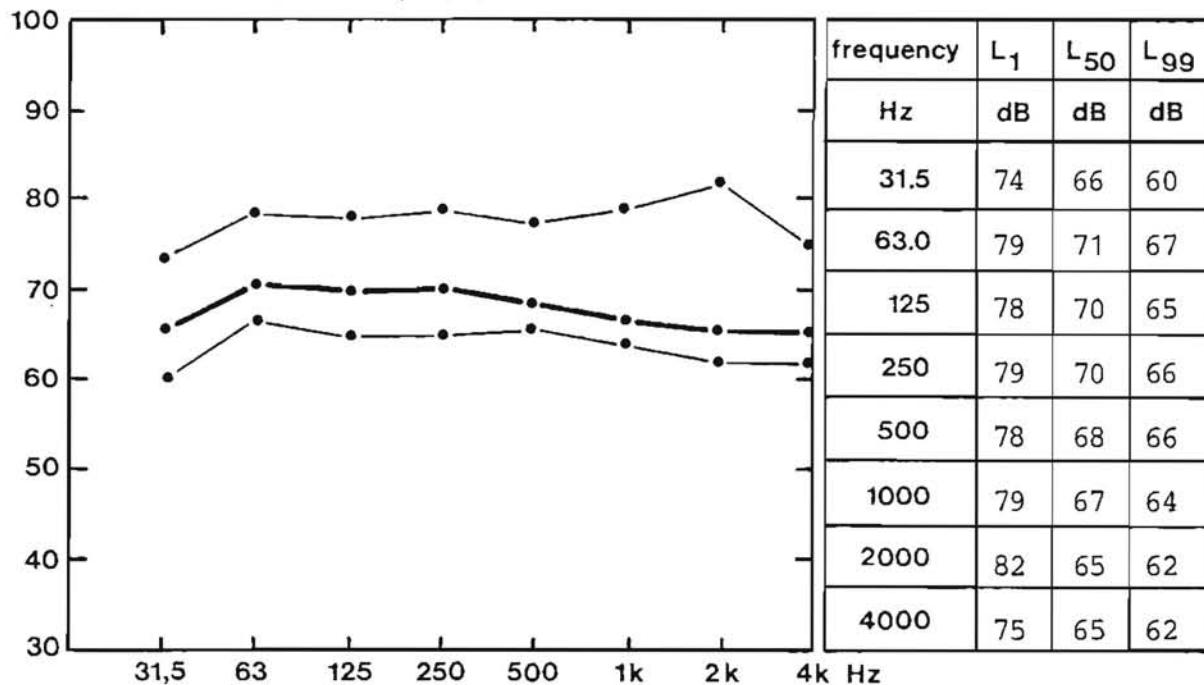
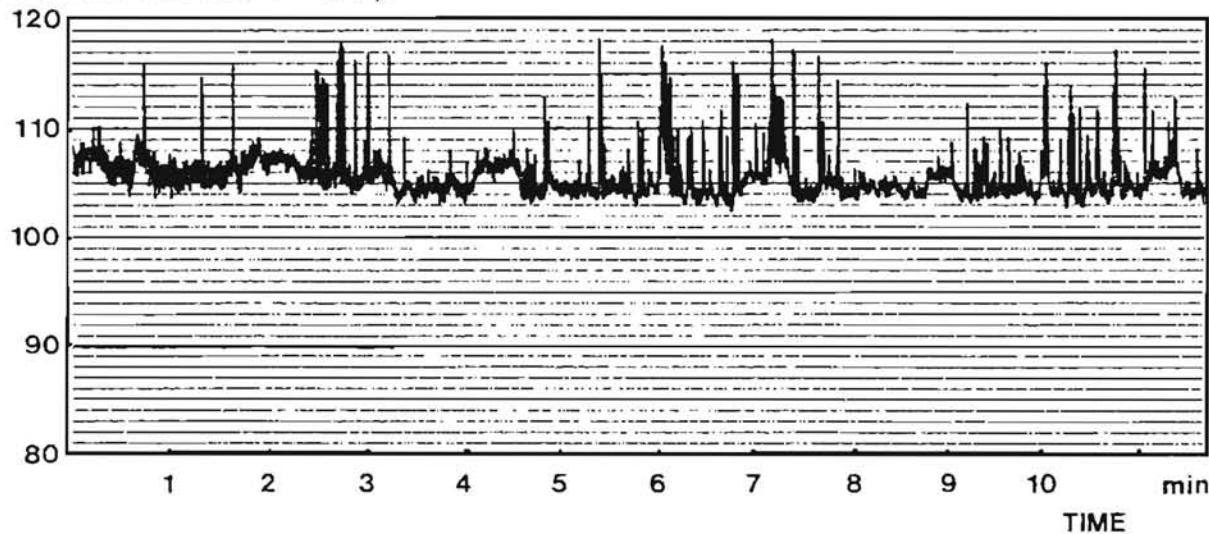


Remarks : Same remarks as for recording 3.



C.10

Recording No. : 6 Time : 14.55
Date : 83.07.01 Water depth : 500 metres
Measurement position: C Hydrophone depth : 9 metres

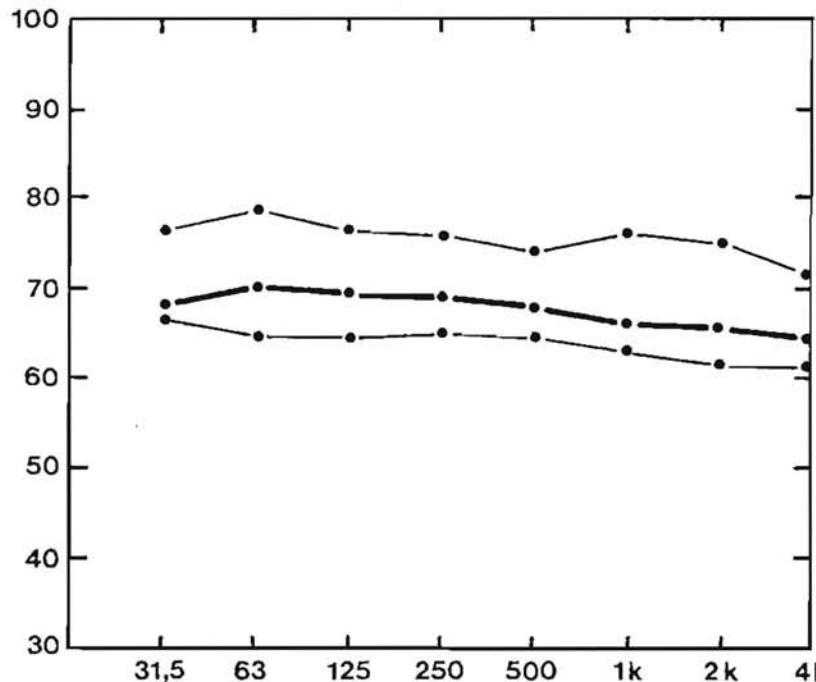
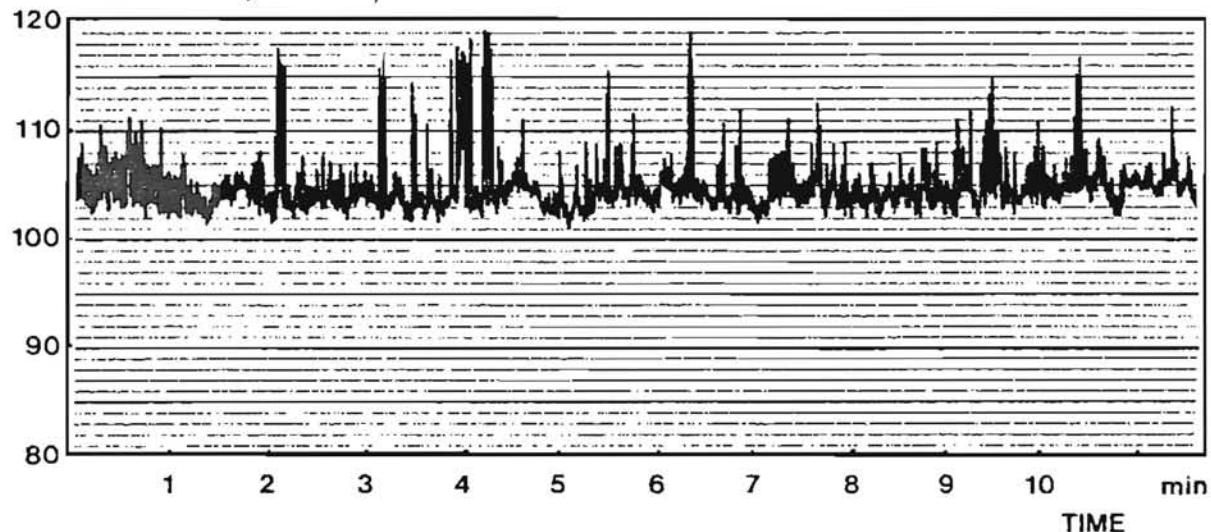
SPECTRUM LEVEL, dB re 1 μ Pa/ $\sqrt{\text{Hz}}$ OVERALL LEVEL, dB re 1 μ Pa

Remarks : Same remarks as for recording 3.
In this recording a bowhead whale was very close to the measuring hydrophone.



C.11

Recording No. : 7 Time : 15.20
Date : 83.07.01 Water depth : 500 metres
Measurement position: C Hydrophone depth : 9 metres

SPECTRUM LEVEL, dB re 1 μ Pa/ $\sqrt{\text{Hz}}$ OVERALL LEVEL, dB re 1 μ Pa

Remarks : Same remarks as for recording 3.



APPENDIX D

Transmission Loss Measurements, Analysis and Results in Details



TRANSMISSION LOSS MEASUREMENTS

The method of the transmission loss measurements are briefly described in section 2.2 and the main results are given in section 4. This Appendix, however, offers a more detailed description of the measuring and analysing procedure. Furthermore, the results for the complete measurements are given.

D.1 Measuring Procedure

The sound transmission loss measurements were performed by detonating explosive charges in the water and simultaneously measuring the pressure level partly with a hydrophone placed close to the explosion ("source hydrophone") and partly with a set of three hydrophones ("receiver hydrophones"), placed at varying distances from the source. The arrangement is shown in Figure D.1.

Blasting caps with a content of one gramme of trinitrotoluene (TNT) were used as explosive sound sources. The charges were ignited electrically at a constant depth of 4 metres below the sea surface. A depth of 4 metres was chosen as this is the approximate depth of the cavitation centre of the propellers of "JOHN A. MACDONALD".

The source hydrophone was placed 2 metres below the explosive charge and the receiver hydrophones were placed at depths of 5, 50 and 100 metres, respectively.

All the shots were detonated at the same depth and with a constant distance to the source hydrophone. The distance between the source and the receiver hydrophone was determined by means of the "Mini Ranger" system. The distances applied are given in Table D.1 below.



Location	Distance				
Location A, Baffin Bay	675 m	1700 m	7770 m	17800 m	35000 m
Location B, Lancaster Sound	1170 m	1800 m	6860 m	14470 m	35200 m

Table D.1.
Distance between the source and the receiver hydrophones during the sound transmission loss measurements.

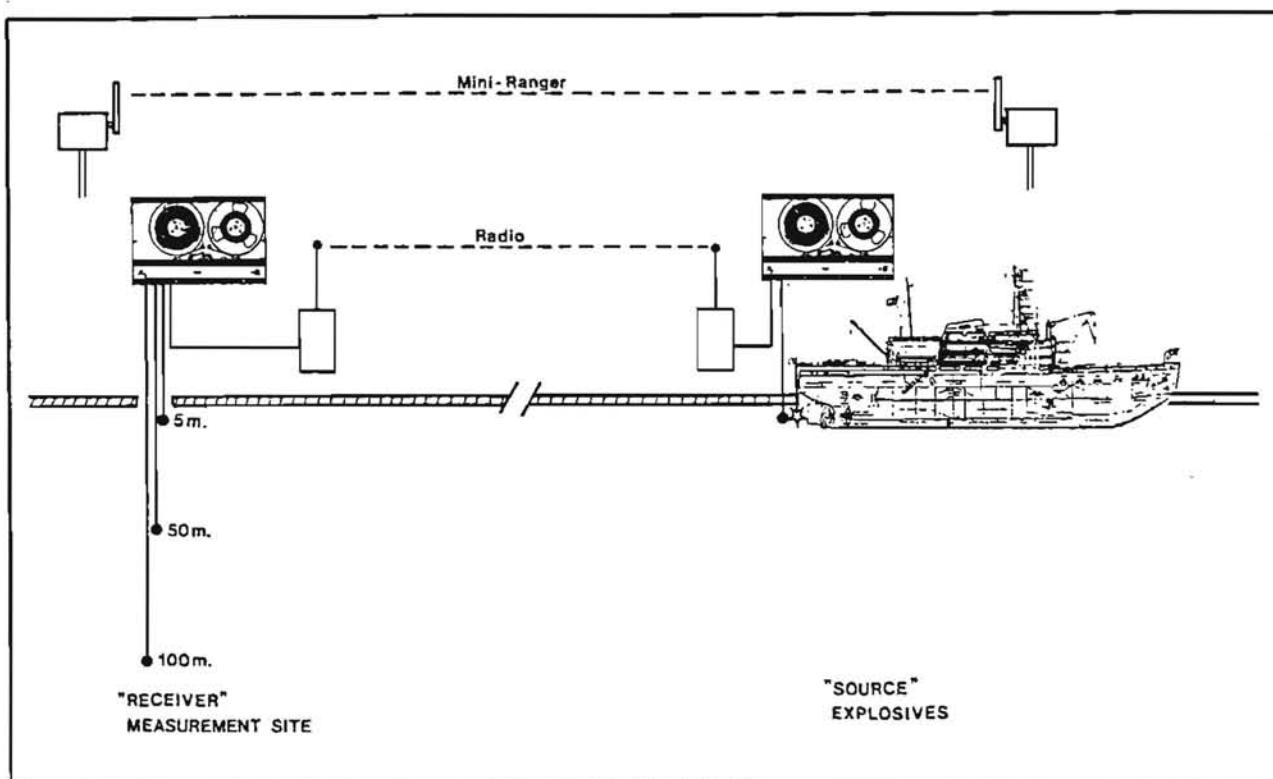


Figure D.1.
Arrangement of the hydrophones at the sound transmission loss measurements.

D.2 The Source Signals

When the blasting cap is detonated, it will generate pressure pulses in the water. A typical signature of the source signal



which can be recorded by the source hydrophone, is illustrated by the pressure time function in Figure D.2. By adding the transmission loss, corresponding to the distance between the shot and the source hydrophone, to the measured signal, the source signal has been corrected to represent a distance of 1 metre from the explosion.

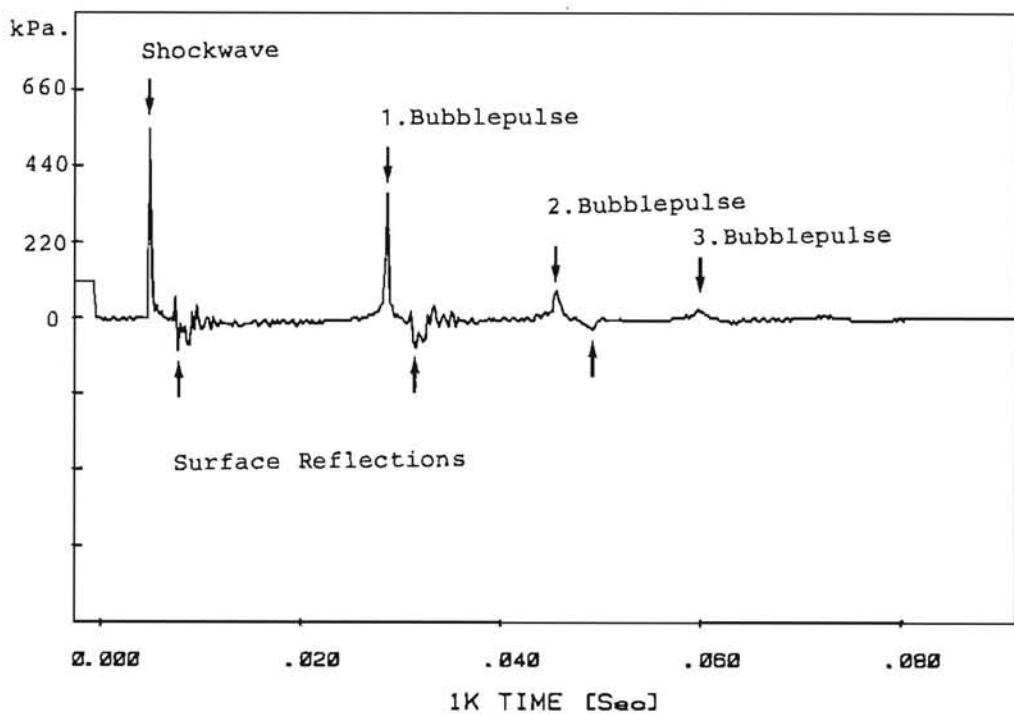


Figure D.2.
Measured pressure time function corrected to represent
a distance of 1 metre from the blasting cap.

In Figure D.2 it can be seen that the signal consists of a number of spikes corresponding to a shock wave and a number of bubble pulses. The sea surface reflections of these pulses are recognized as the negative going spikes delayed by the travel time introduced by the extra distance of twice the source depth. Correspondingly the amplitude of the surface reflections has been attenuated according to the difference in travel length. The positive pressure pulse is reflected as a negative pressure pulse because of the 180 degree phase shift at the "acoustical soft"



surface. The time difference between the shock wave and the first bubble pulse (approximately 25 ms) varies a little for the different shots due to minor changes in the depth when ignited.

The surface reflections of the pulses will affect the shape of the frequency spectrum for the resulting pulse signal arriving at a certain receiver location. This means that the shallow location of the source will result in a source strength directivity, corresponding to a dipole source.

By measurements and calculation of sound transmission loss, it is most convenient to include this directivity in the transmission loss and refer to the source strength of an equivalent omnidirectional monopole source.

The equivalent monopole source strength of the explosives can be determined during the signal analysis by removing all the surface reflections in the digitized pressure time function and consequently obtain the frequency spectrum by using an FFT routine. The effect of this editing is illustrated in Figure D.3, which shows an example of the frequency spectrum for a source shot with and without surface reflected pulses in the corresponding time function.

The examples used in Figure D.3 have been taken from a previous investigation in which the source hydrophone was placed at a greater distance below the blasting cap. With that arrangement the difference in travel length is smaller and the interaction between the direct and the surface reflected wave therefore more pronounced.

The influence of the surface reflected waves is seen in Figure D.3 as an amplitude variation in the frequency spectrum with repeated dips and maxima. The amplitude variations are due to the "Lloyd-Mirror effect" caused by interference between the direct wave and the surface reflected wave. These variations are not found in the frequency spectrum when the surface reflections are

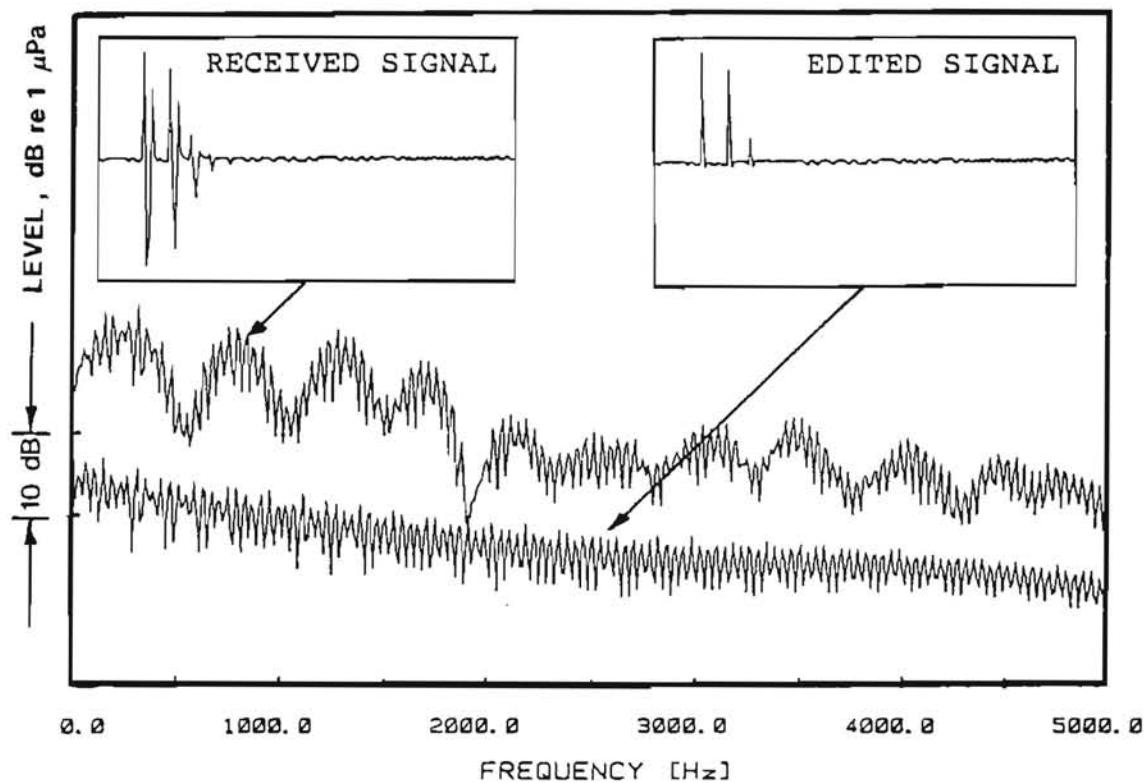
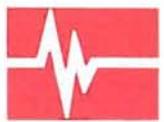


Figure D.3.

Example of frequency spectrum derived from the pressure time function of a source shot with and without surface reflections removed. To ease the comparison, the two curves have been separated by 10 dB. The curves have been obtained from a previous investigation applying a different hydrophone depth.

removed as seen in Figure D.3. The smaller fluctuations, which are repeated with a narrow frequency interval, are mainly due to the time interval between the shock wave and the first bubble pulse.

The sound transmission loss measurements have been analyzed in the frequency intervals 0-500 Hz and 0-5000 Hz. Figure D.4 shows the free field source spectrum in the two frequency intervals for a typical explosion corrected for the distance to the source hydrophone.

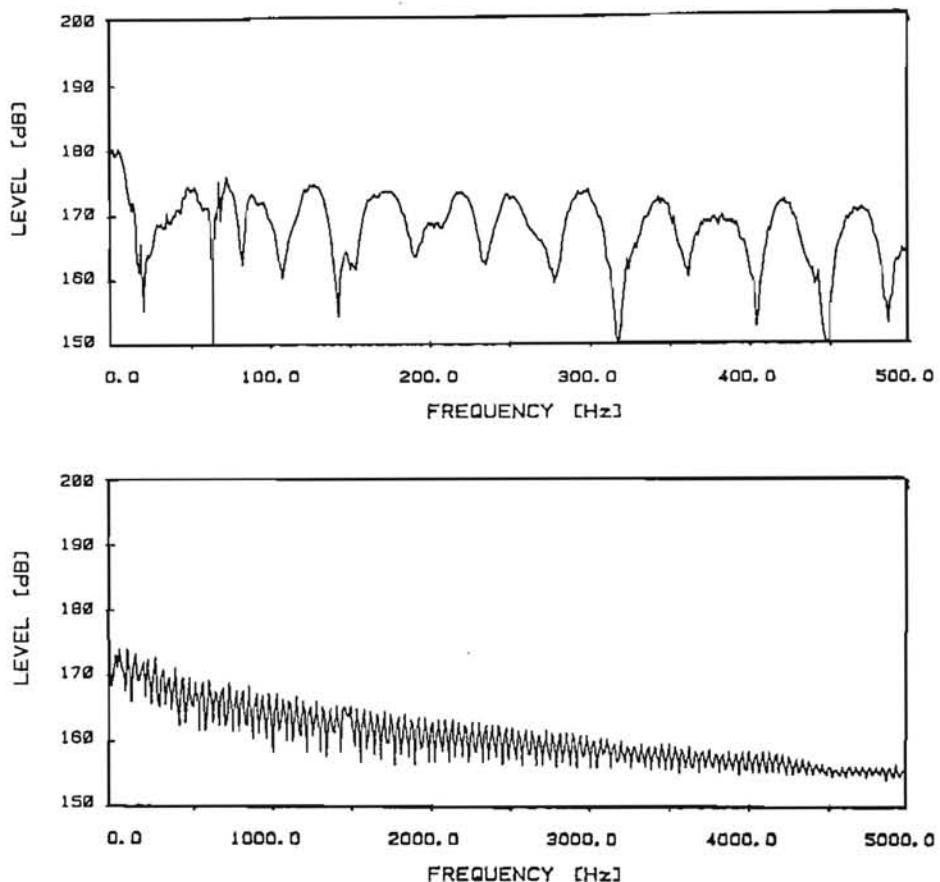


Figure D.4.

Free field source spectrum for the explosive charge referring to a distance of 1 metre.

The repeated dips and maxima caused by the bubble pulse can be seen clearly in Figure D.4. The frequency interval is 45 Hz corresponding to a time interval of 22 ms between the shock wave and the first bubble pulse.

D.3 The Received Signals

Examples of the pressure time functions for the shots measured at the receiver hydrophones are given in Figures D.5 and D.6.

Figure D.5 illustrates the differences in the received signal of the same shot recorded at the three different depths of 5, 50 and 100 metres.



D.8

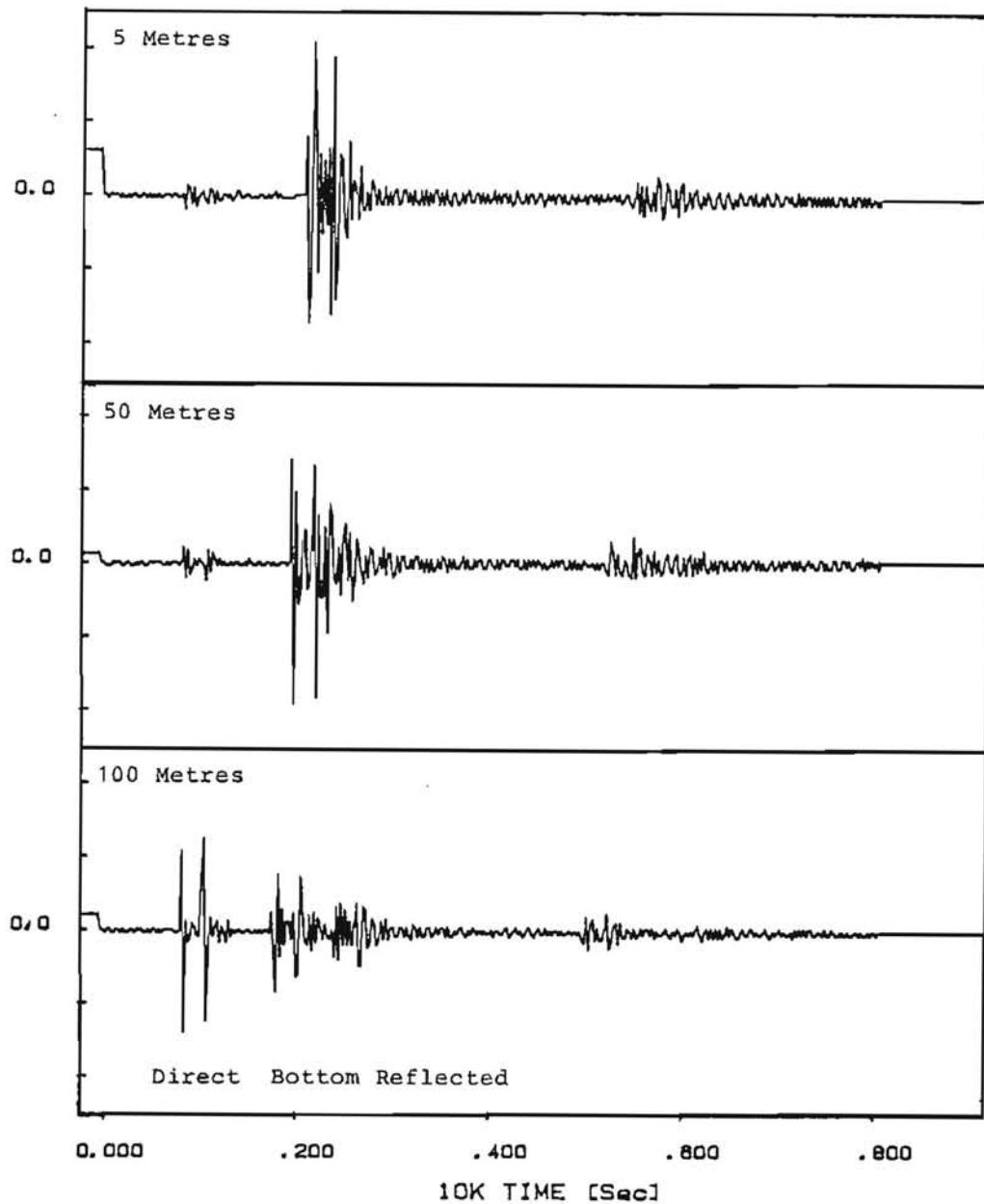


Figure D.5.

Received pressure time functions measured in Baffin Bay (Location A) at a distance of 1700 m. Hydrophone depths: 5, 50 and 100 metres.

For the shallow hydrophone at the depth of 5 metres, it can be seen that the direct transmitted signal is very weak due to the surface effect while the amplitude of the bottom reflected signal is much higher. At the deeper hydrophones the amplitude of the direct wave increases compared with the bottom reflected wave,



again corresponding to the directivity of the dipole source caused by the surface. At longer distances the direct transmitted wave will diminish and only the bottom reflected waves will determine the received signal.

This effect is illustrated in Figure D.6 where the received pressure time functions of a shot measured at the depth of 50 metres are given for all five distances from the measurement in Lancaster Sound.

Figure D.6 illustrates how the multiple reflected waves at the long distances form a "reverbant" field. The direct transmitted signal is not detectable at the long ranges. The reason for the high amplitude of the direct transmitted signal at the distance of 1880 m is probably the upward refraction of the sound waves as also illustrated in the Ray-trace diagram in Figure B.15.

D.4 Transmission Loss

The sound transmission loss is calculated by subtracting the spectrum of the monopole source strength of the shot from the spectrum of the received signal at the varying distances. The narrow-band frequency analysis of the sound transmission losses are given in Figures D.7 to D.22. These figures show the sound transmission losses in the frequency ranges 0-500 Hz and 0-5000 Hz for every shot at the three hydrophone depths of 5, 50 and 100 metres and for the two measurement sites, Baffin Bay and Lancaster Sound. Where more than one shot is available at a distance, the results for all shots are presented.

In Figures D.23 - D.35 the average sound transmission losses are presented in 1/3-octave frequency bands as a function of the distance. The transmission loss in 1/3-octave frequency bands are found from the narrow-band analysis applying a smoothing procedure and an average on energy basis. Where more than one shot is available at a distance, the average transmission loss has been calculated on the basis of the results from all the shots at this distance.



D.10

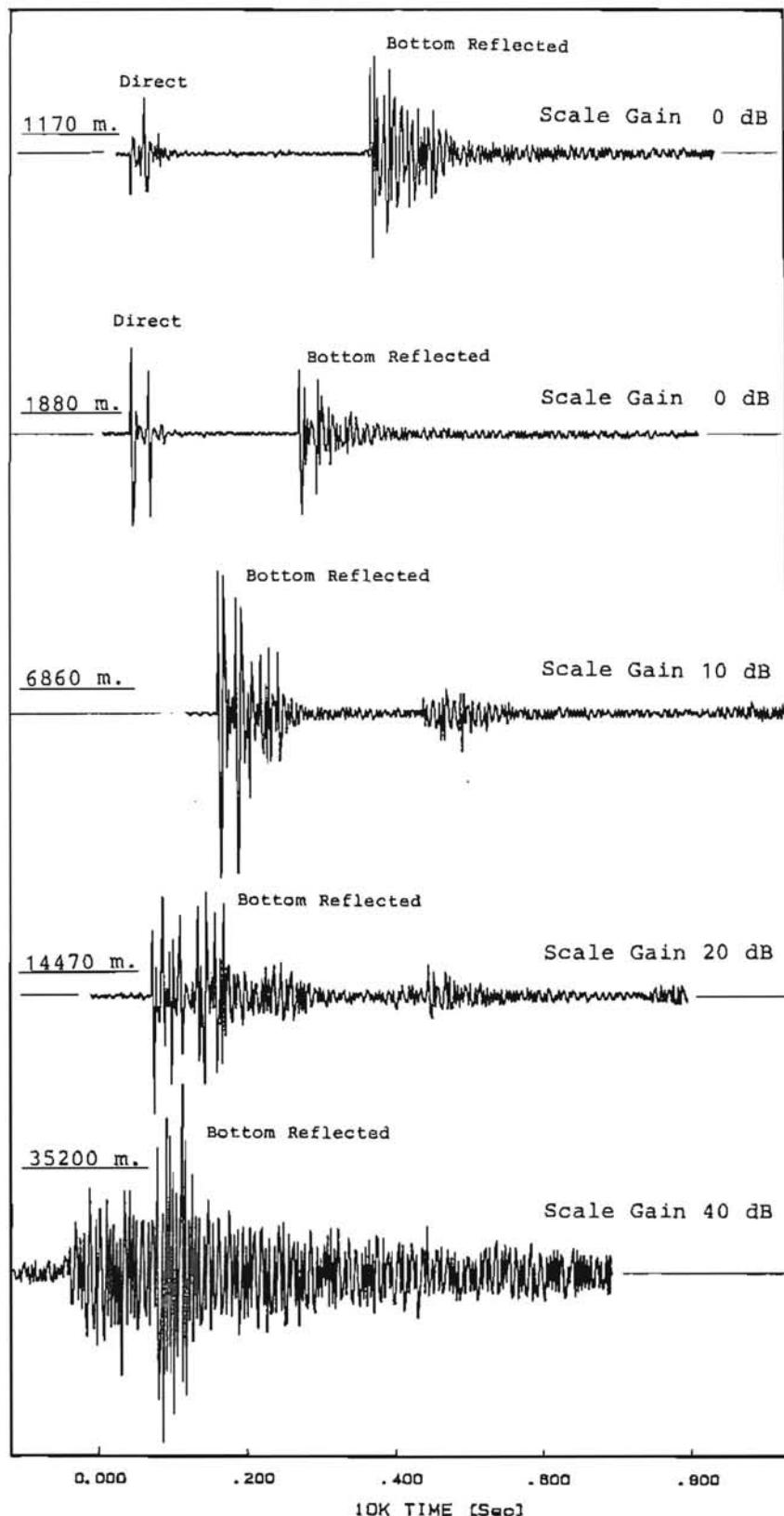
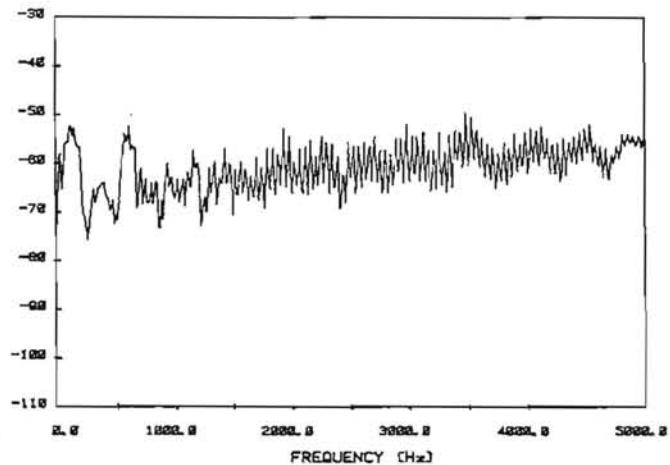
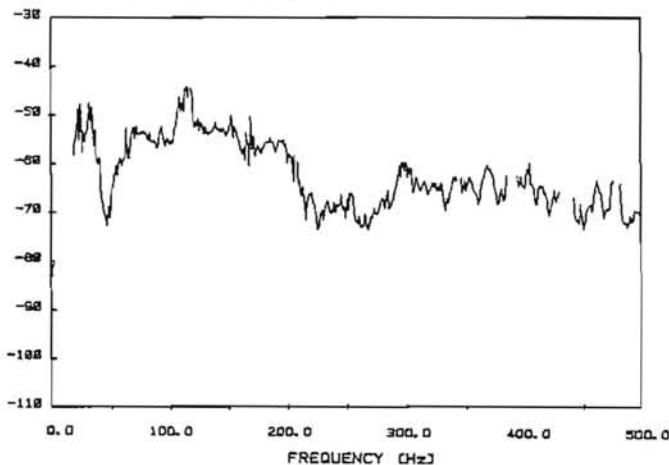


Figure D.6.
Pressure time functions measured in Lancaster Sound
(Location B) at the five different distances. Hydro-
phone depth: 50 metres.

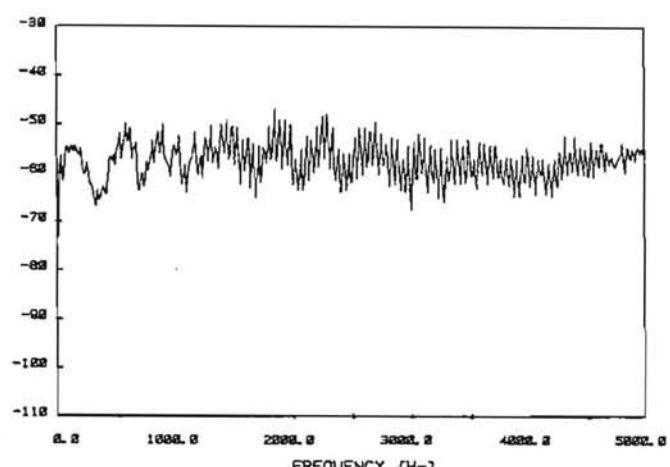
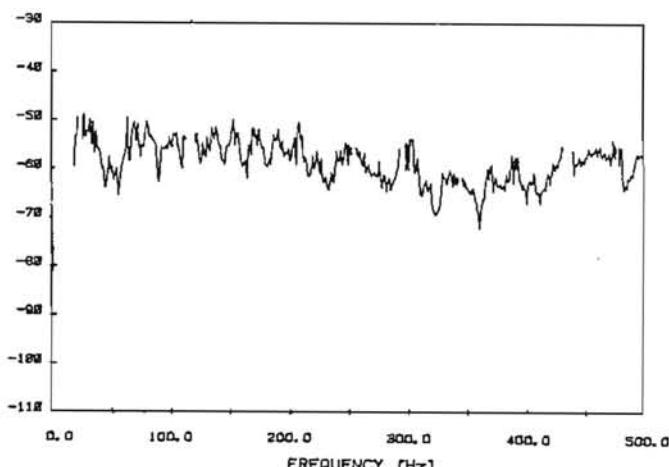


D.11

Receiver Depth 5 m :



Receiver Depth 50 m :



Receiver Depth 100 m :

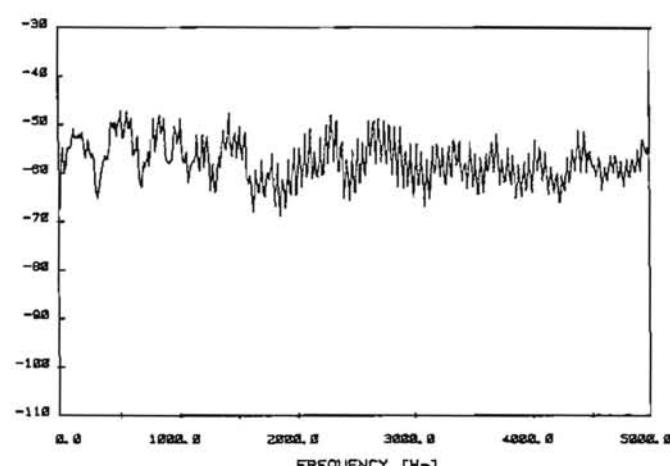
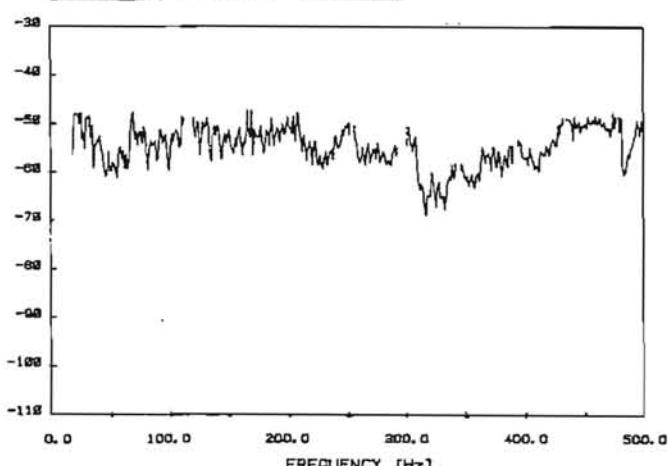


Figure D.7.

Measured transmission loss in Baffin Bay, Location A.
Source depth: 4 metres. Water depth : approx. 400 metres.
Distance between source and receiver: 675 metres.



D.12

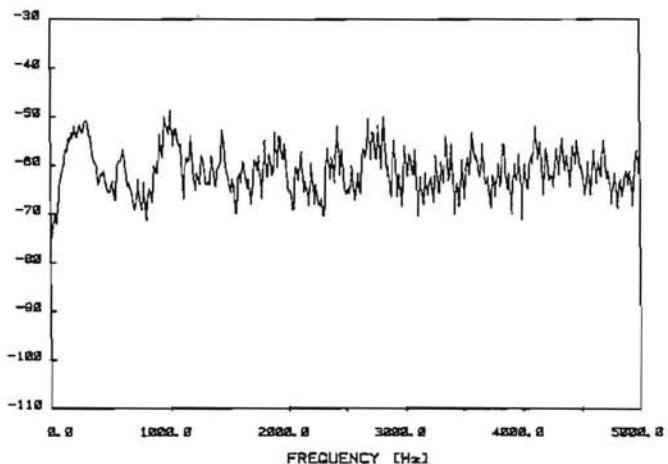
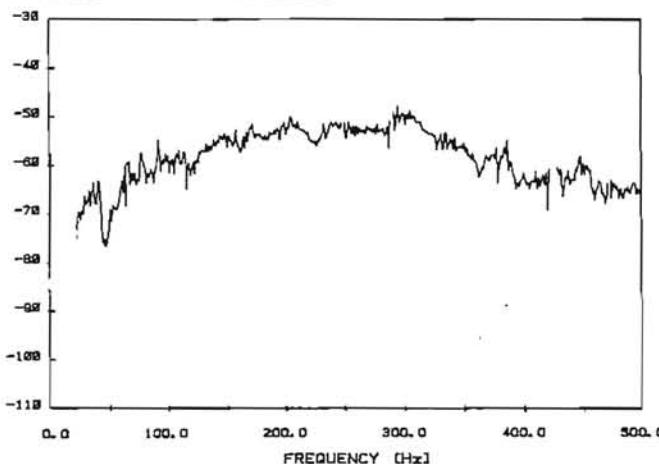
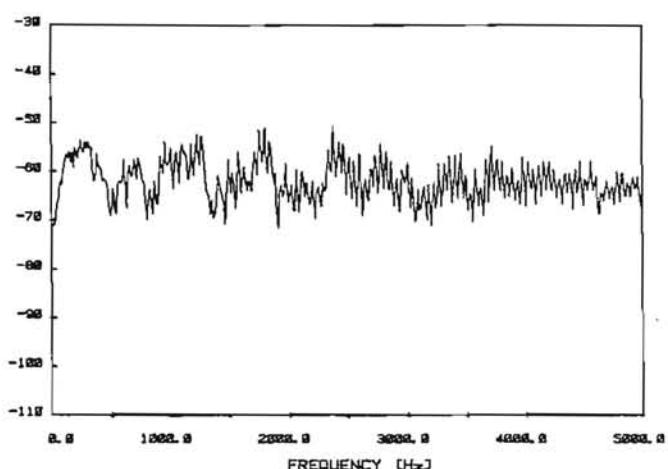
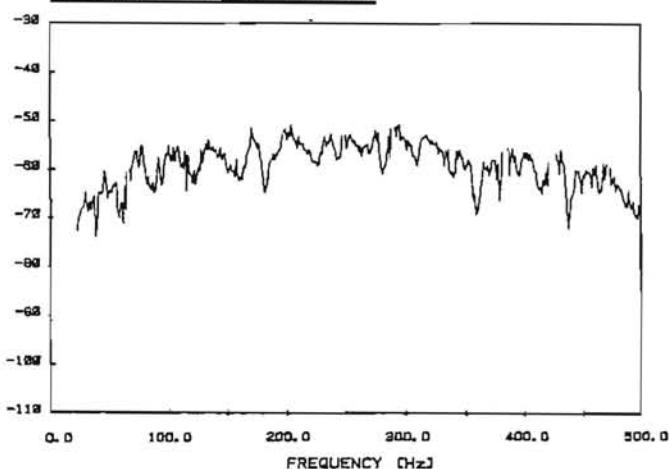
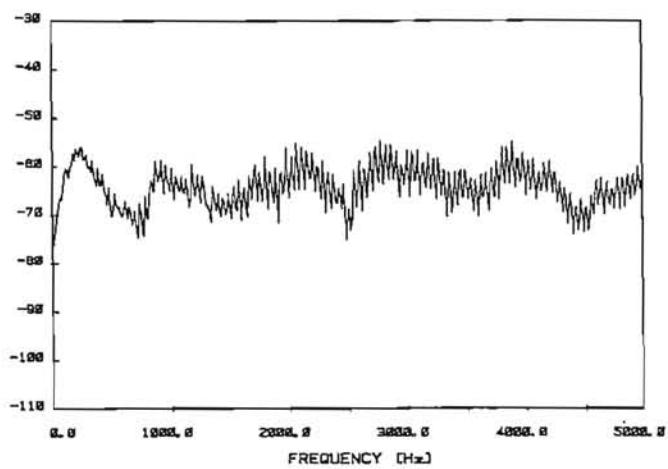
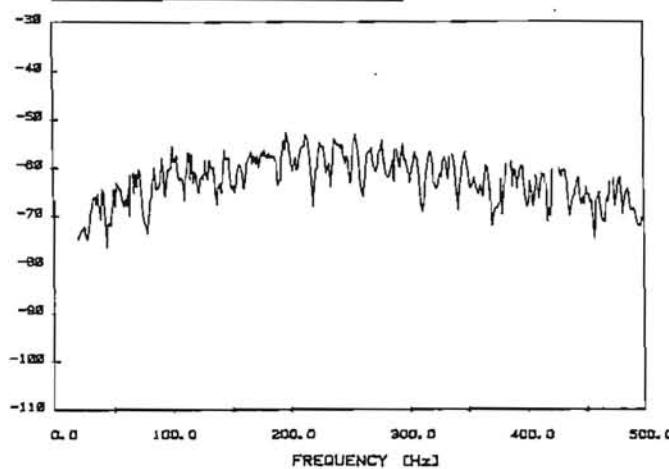
Receiver Depth 5 m :Receiver Depth 50 m :Receiver Depth 100 m :

Figure D.8.

Measured transmission loss in Baffin Bay, Location A.
Source depth: 4 metres. Water depth : approx. 400 metres.
Distance between source and receiver: 1700 metres.



D.13

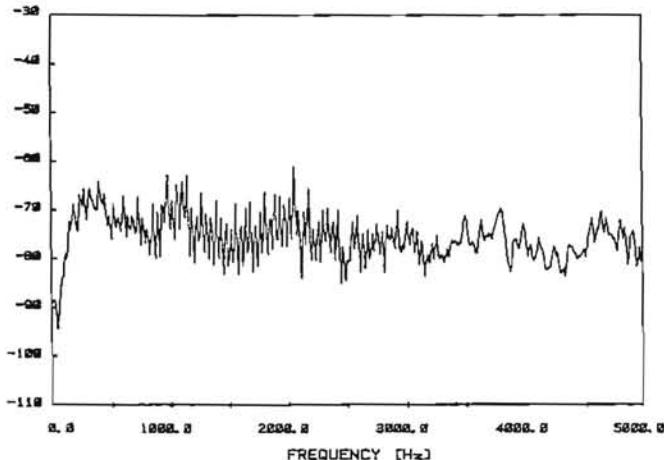
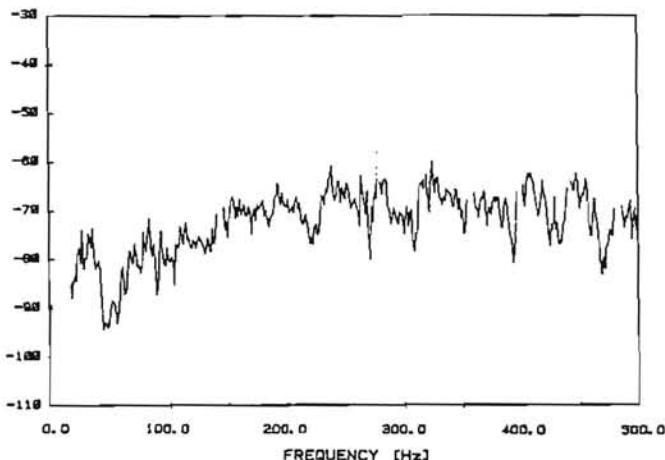
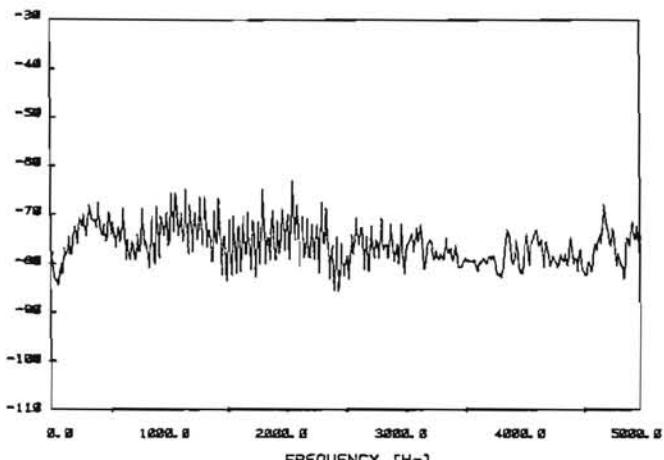
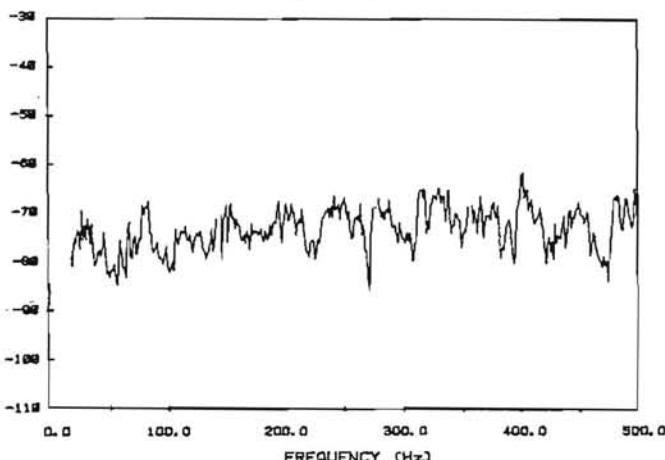
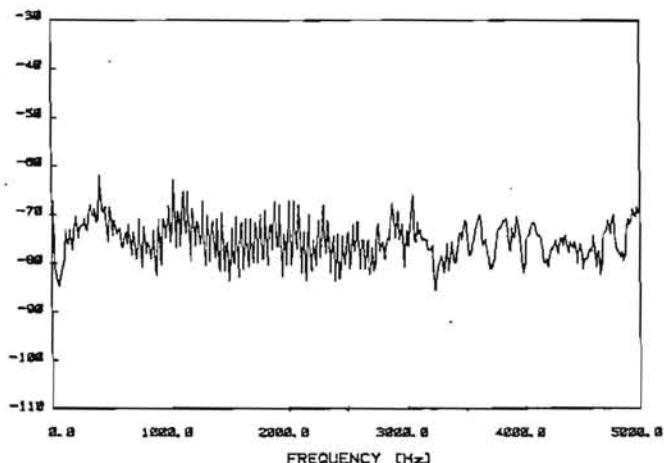
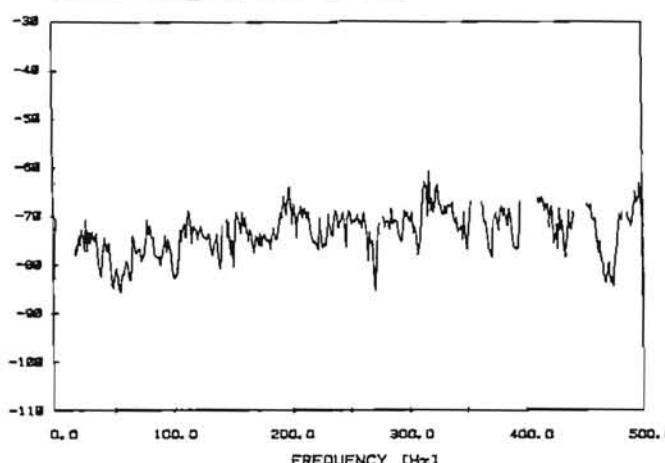
Receiver Depth 5 m :Receiver Depth 50 m :Receiver Depth 100 m :

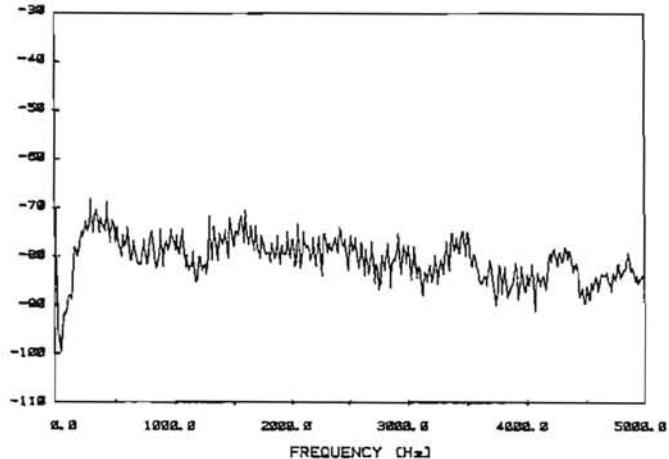
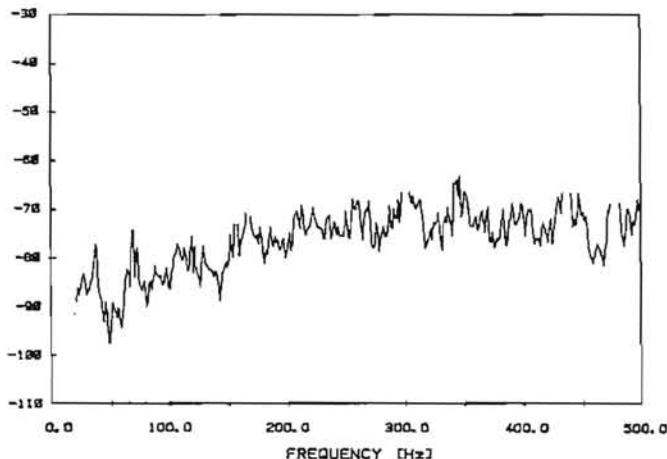
Figure D.9.

Measured transmission loss in Baffin Bay, Location A.
Source depth: 4 metres. Water depth : approx. 400 metres.
Distance between source and receiver: 7770 metres.

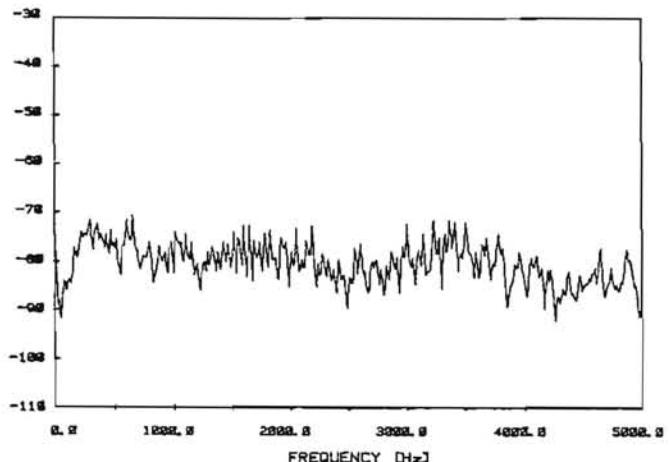
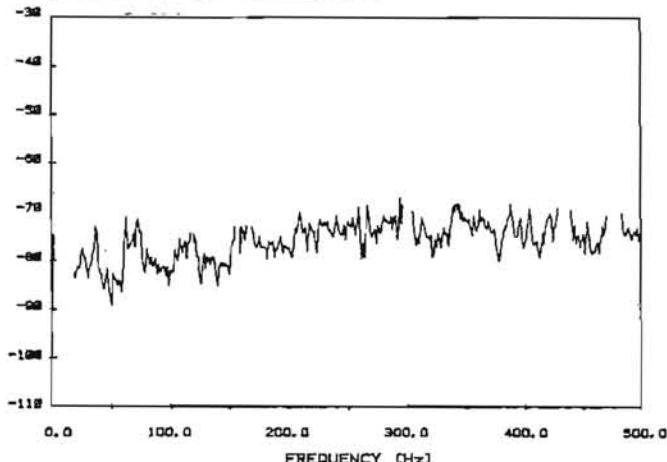


D.14

Receiver Depth 5 m :



Receiver Depth 50 m :



Receiver Depth 100 m :

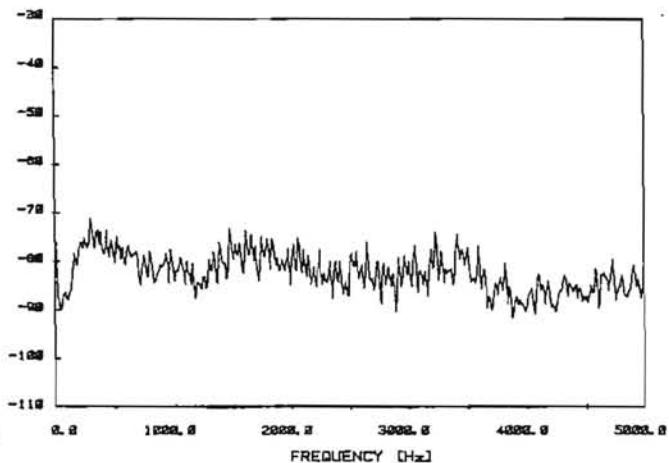
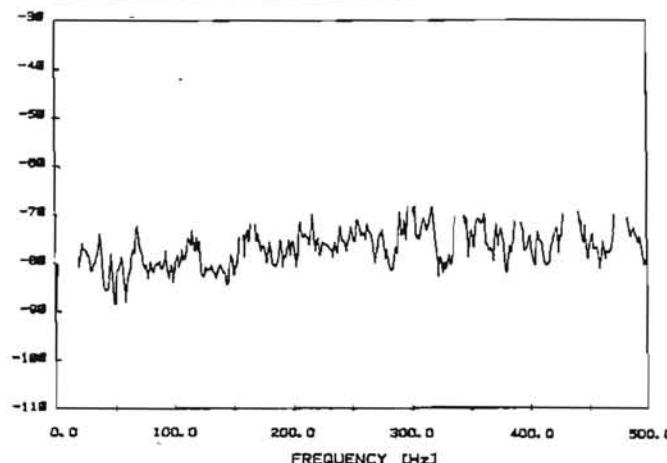


Figure D.10.

Measured transmission loss in Baffin Bay, Location A.
Source depth: 4 metres. Water depth : approx. 400 metres.
Distance between source and receiver: 17800 metres.



D.15

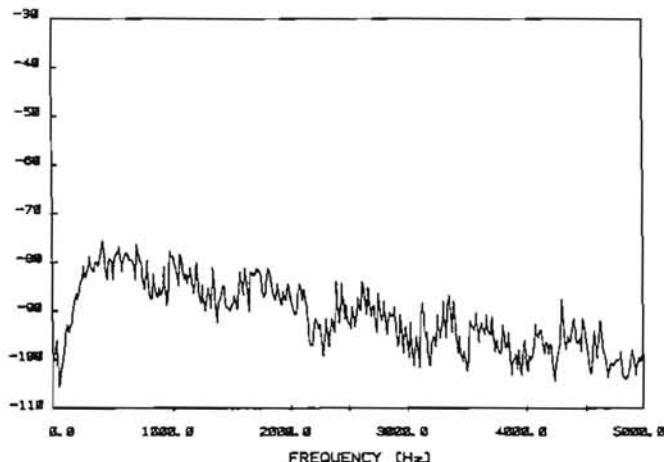
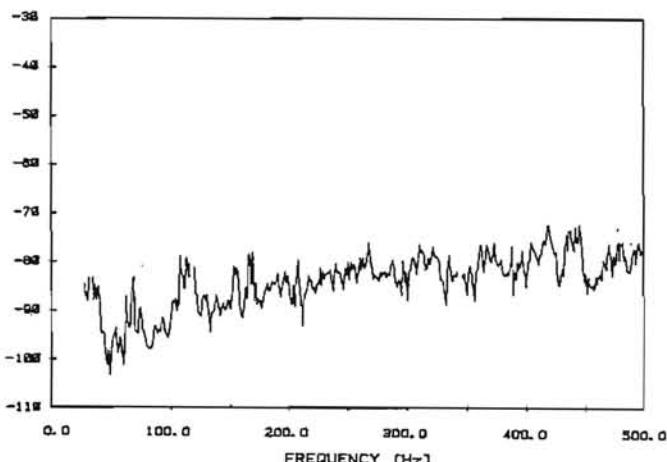
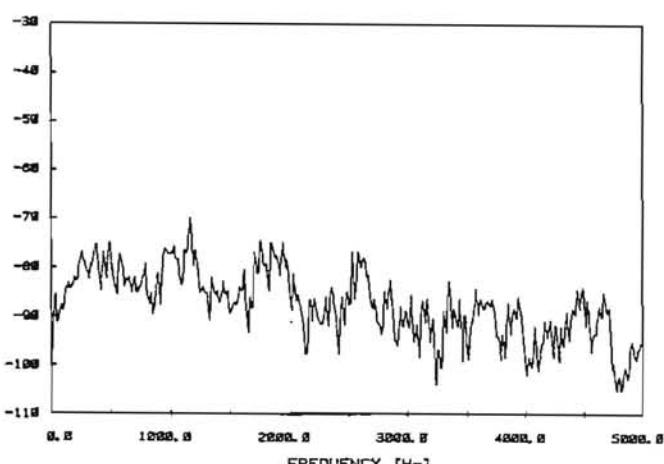
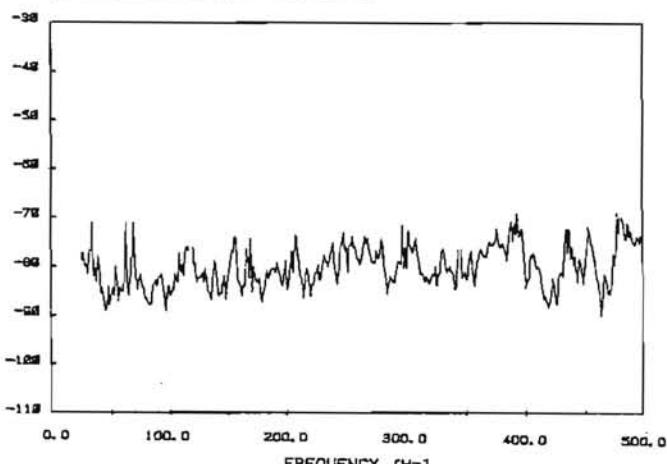
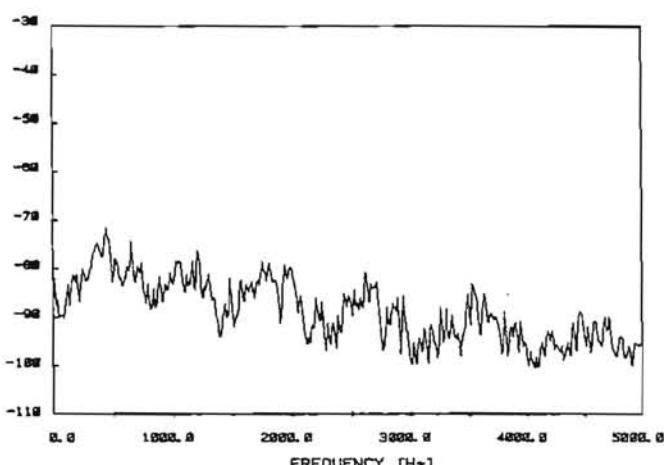
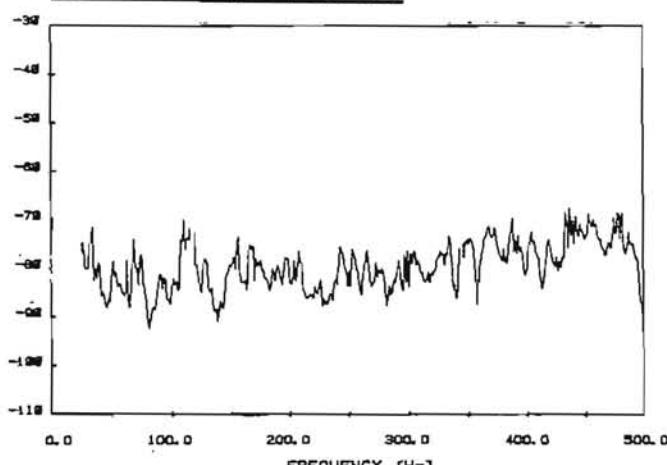
Receiver Depth 5 m :Receiver Depth 50 m :Receiver Depth 100 m :

Figure D.11.

Measured transmission loss in Baffin Bay, Location A.
Source depth: 4 metres. Water depth : approx. 400 metres.
Distance between source and receiver: 35000 metres.



D.16

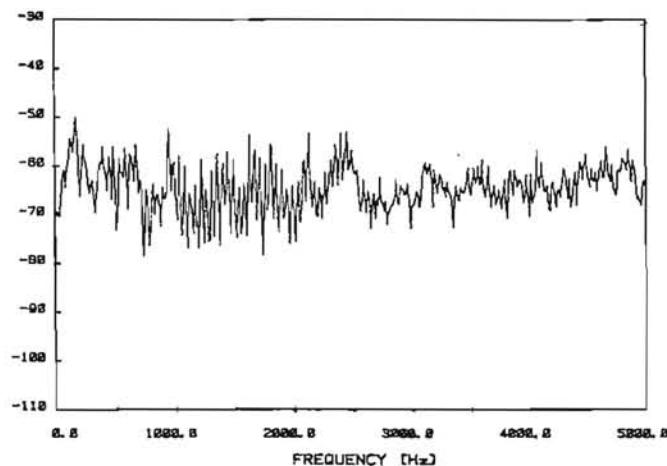
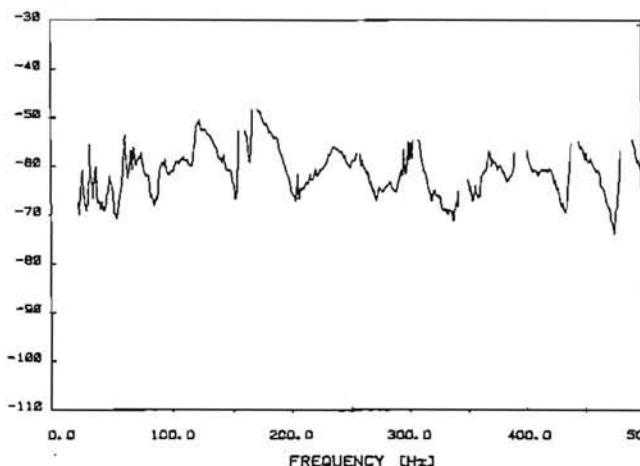
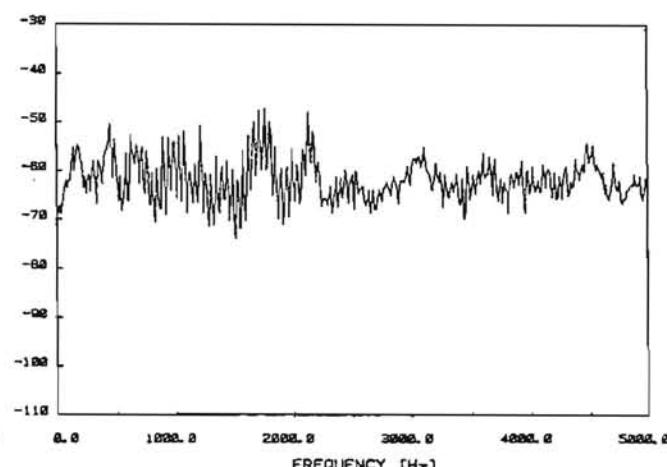
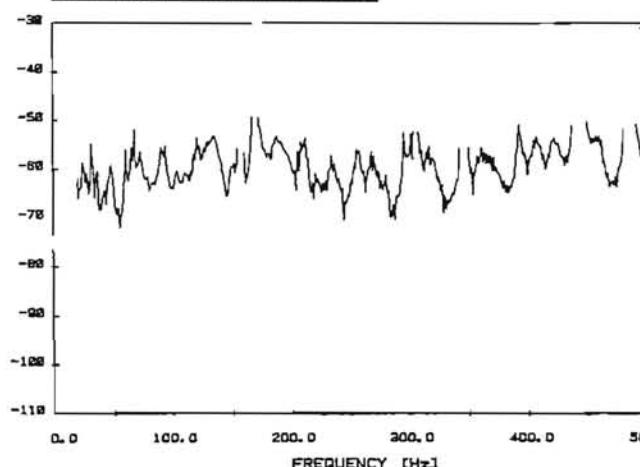
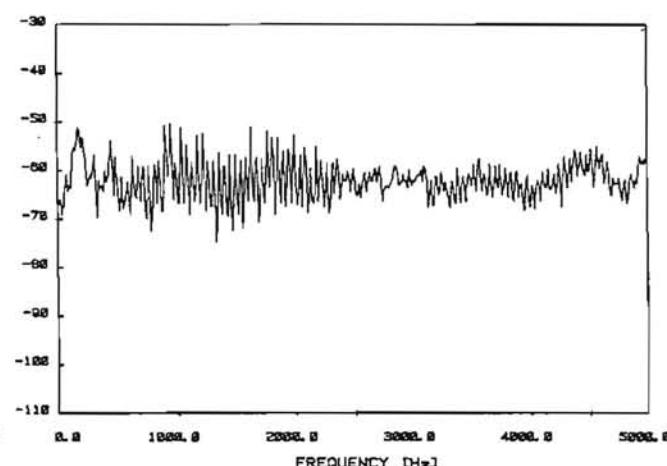
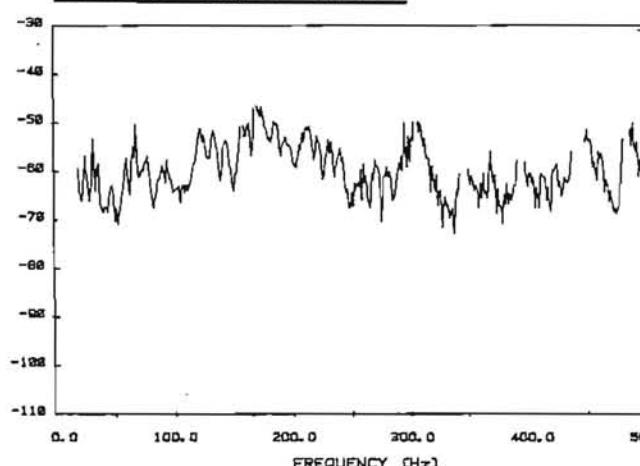
Receiver Depth 5 m :Receiver Depth 50 m :Receiver Depth 100 m :

Figure D.12.

Measured transmission loss in Lancaster Sound, Location B.
Source depth: 4 metres. Water depth : approx 600 metres.
Distance between source and receiver: 1170 metres (No. 1).



D.17

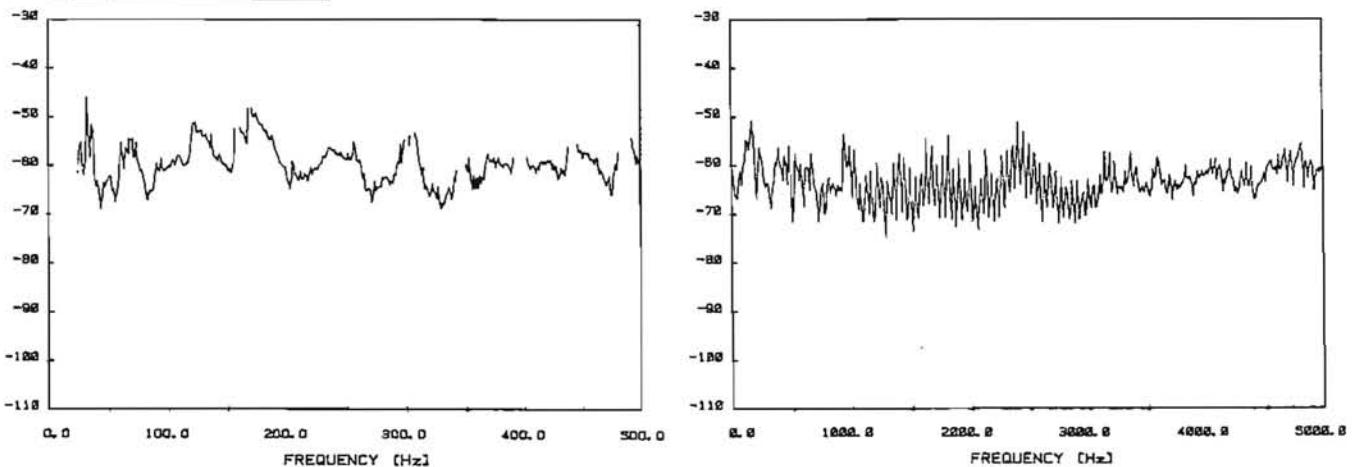
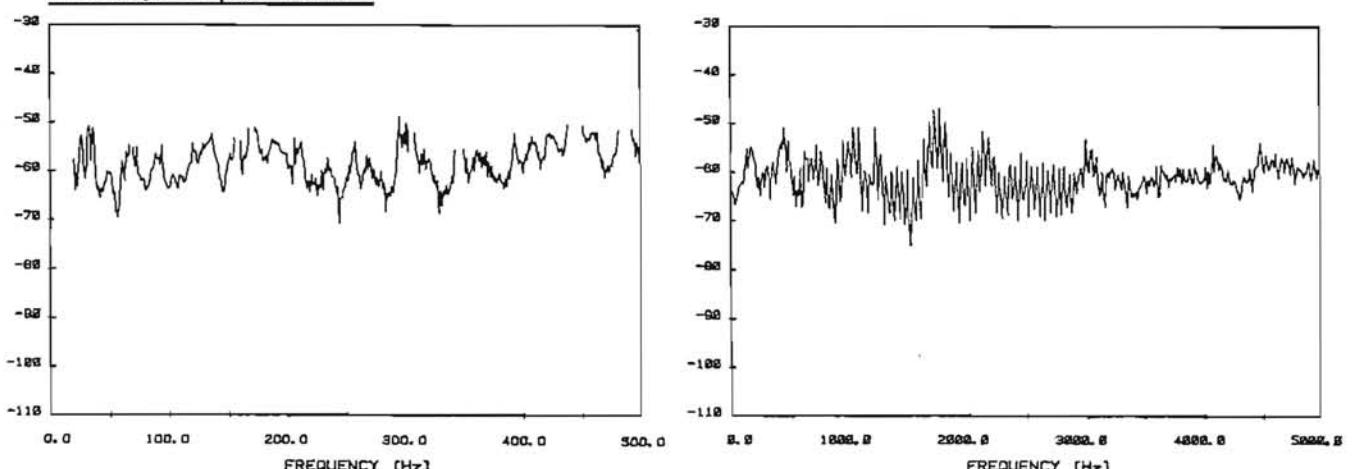
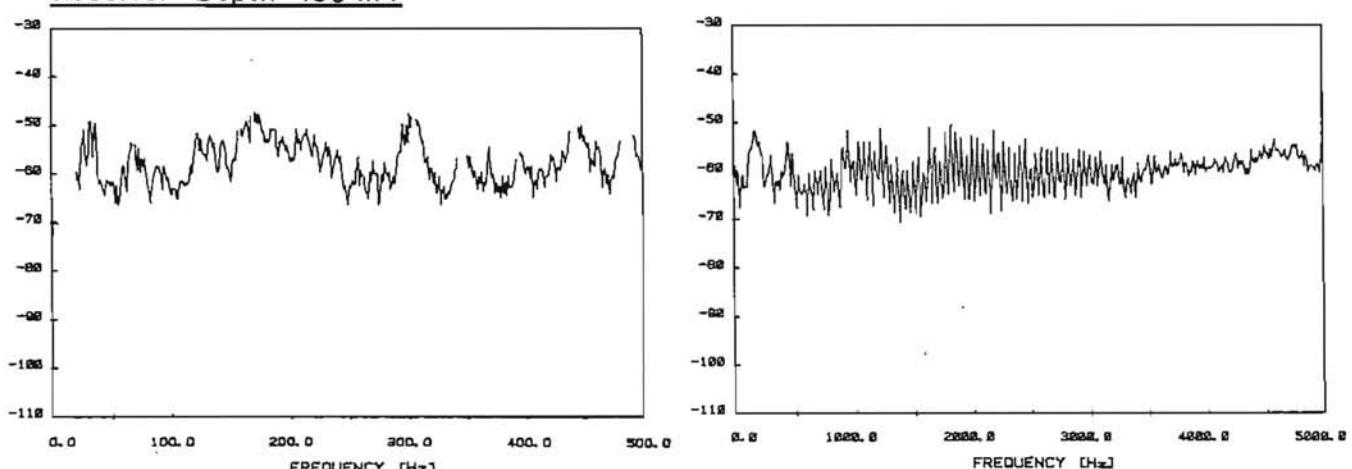
Receiver Depth 5 m :Receiver Depth 50 m :Receiver Depth 100 m :

Figure D.13.

Measured transmission loss in Lancaster Sound, Location B.
Source depth: 4 metres. Water depth : approx. 600 metres.
Distance between source and receiver: 1170 metres (No. 2).



D.18

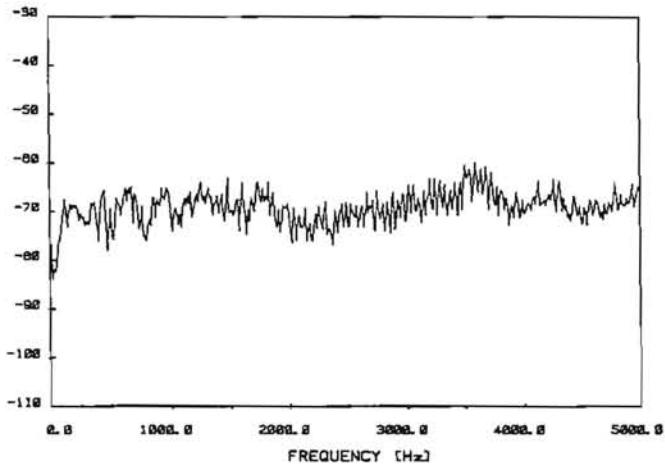
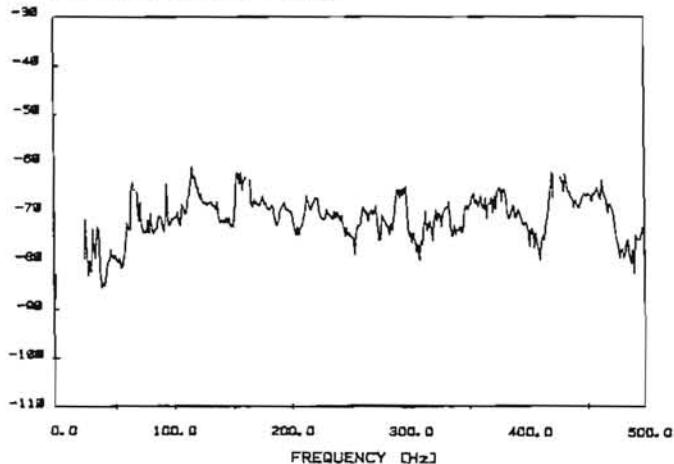
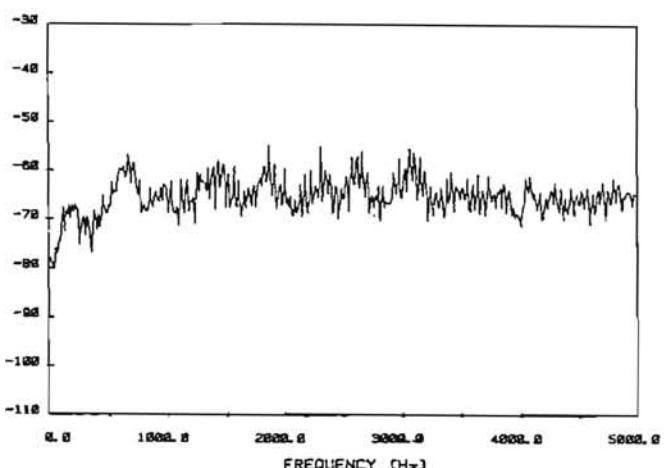
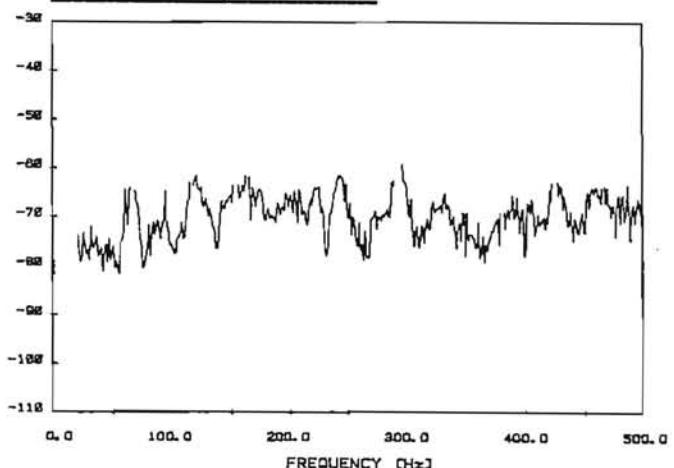
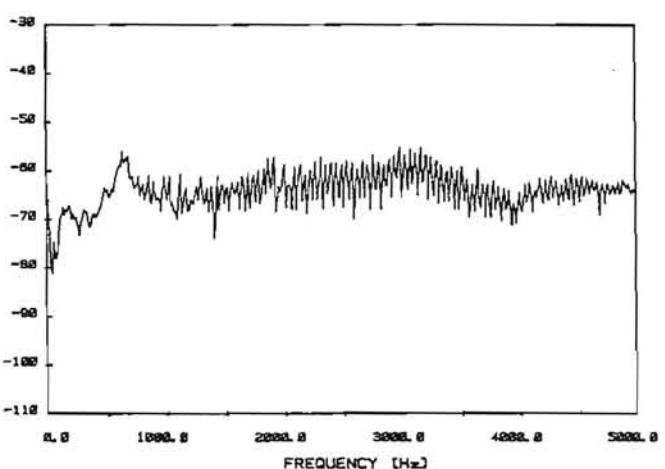
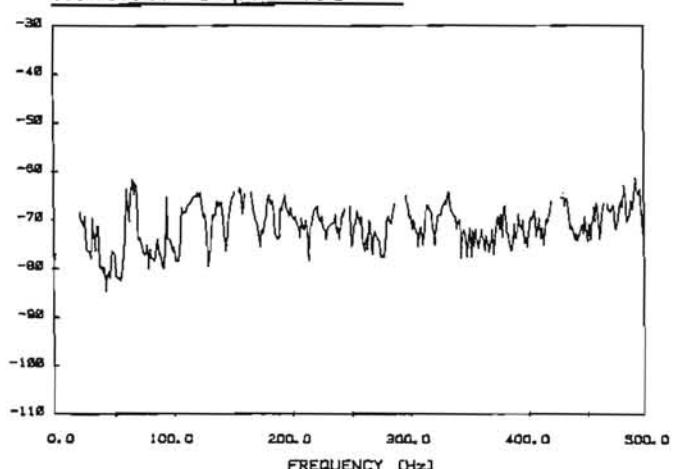
Receiver Depth 5 m :Receiver Depth 50 m :Receiver Depth 100 m :

Figure D.14.

Measured transmission loss in Lancaster Sound, Location B.
Source depth: 4 metres. Water depth : approx. 600 metres.
Distance between source and receiver: 1880 metres (No. 1).



D.19

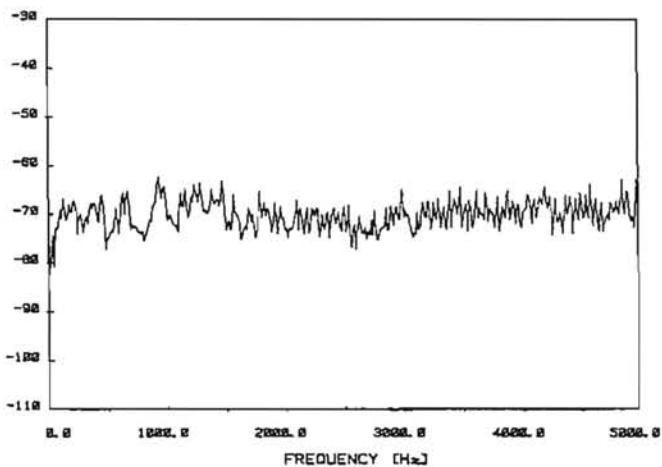
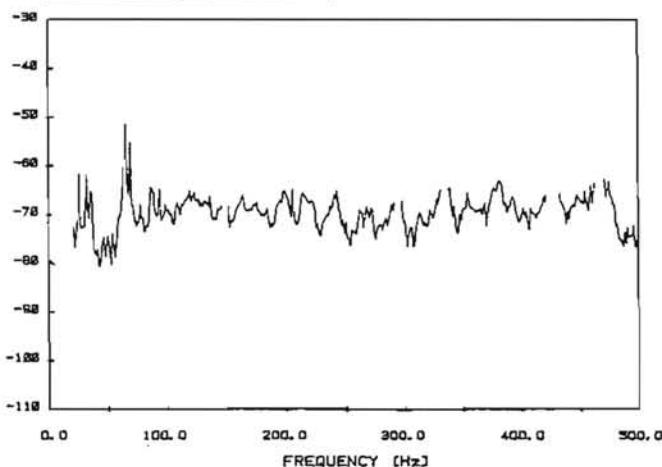
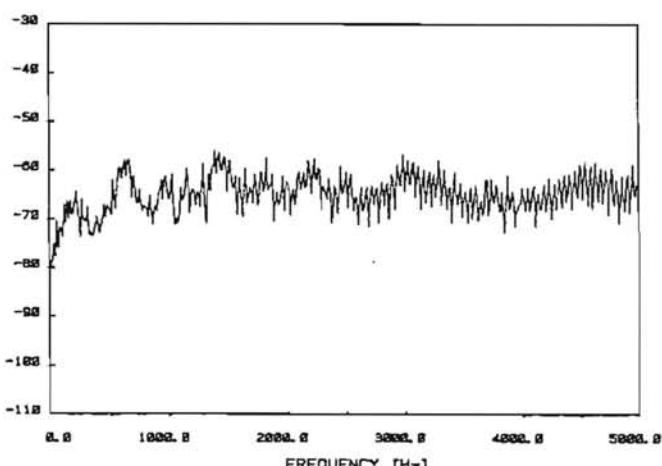
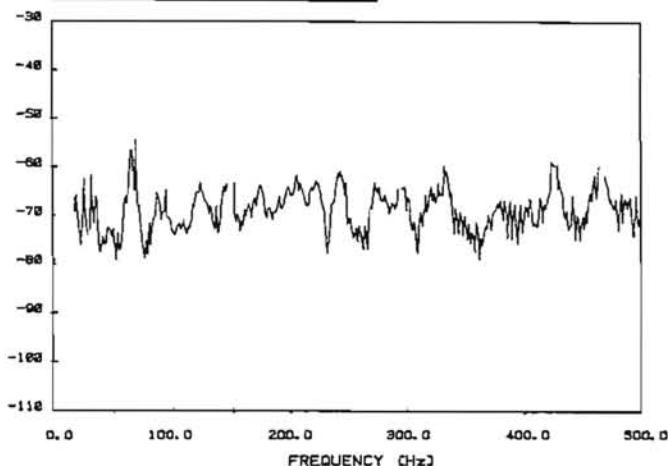
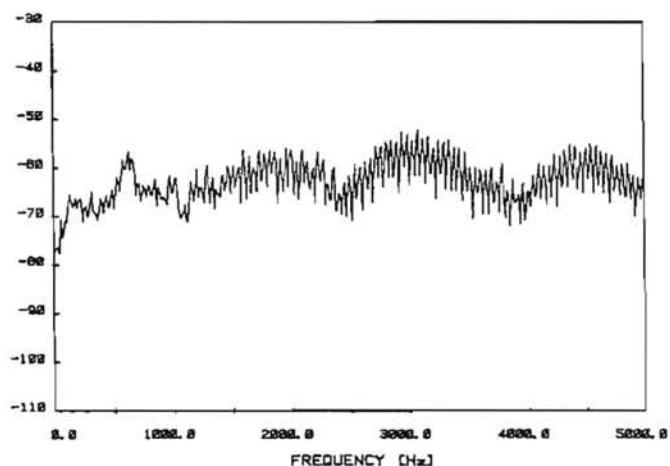
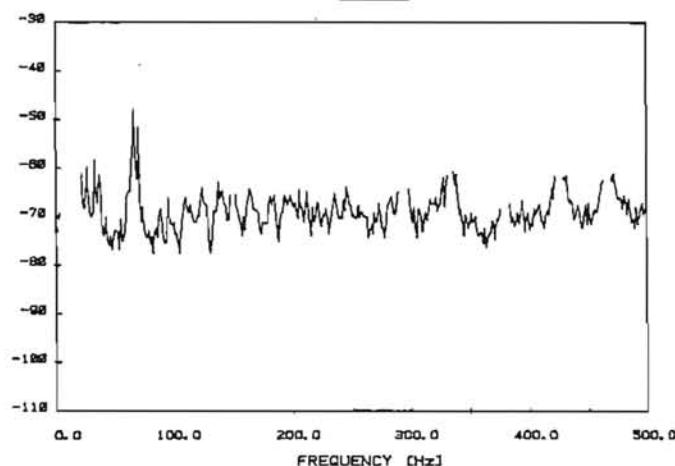
Receiver Depth 5 m :Receiver Depth 50 m :Receiver Depth 100 m :

Figure D.15.

Measured transmission loss in Lancaster Sound, Location B.
Source depth: 4 metres. Water depth : approx. 600 metres.
Distance between source and receiver: 1880 metres (No. 2).



D.20

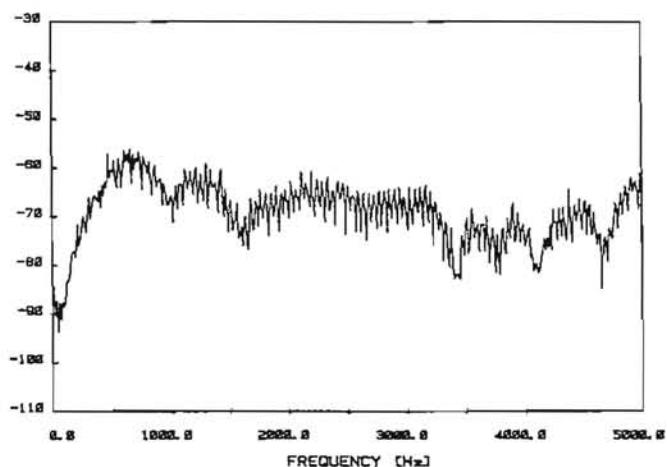
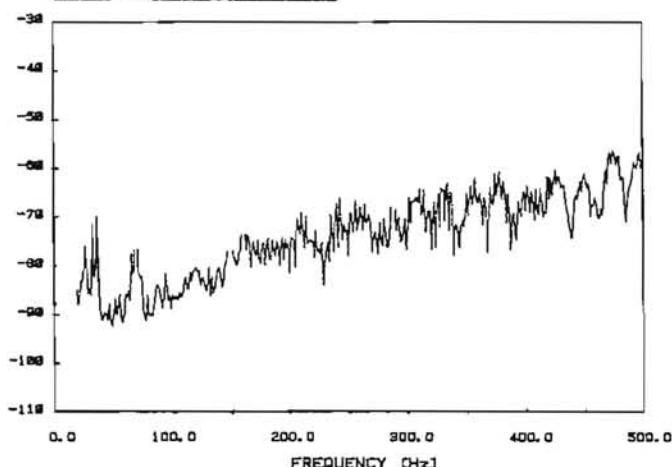
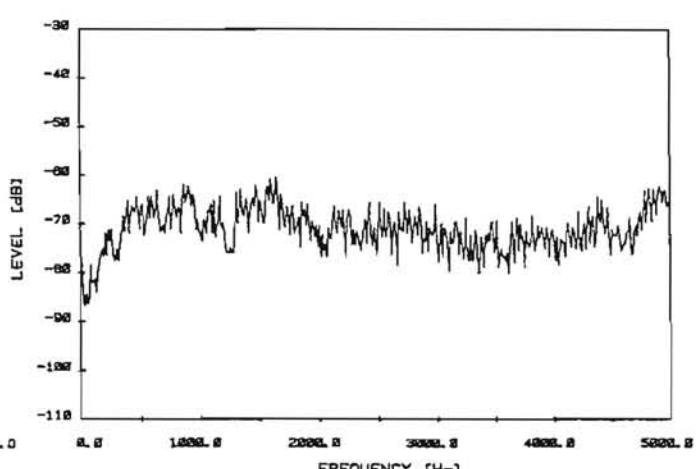
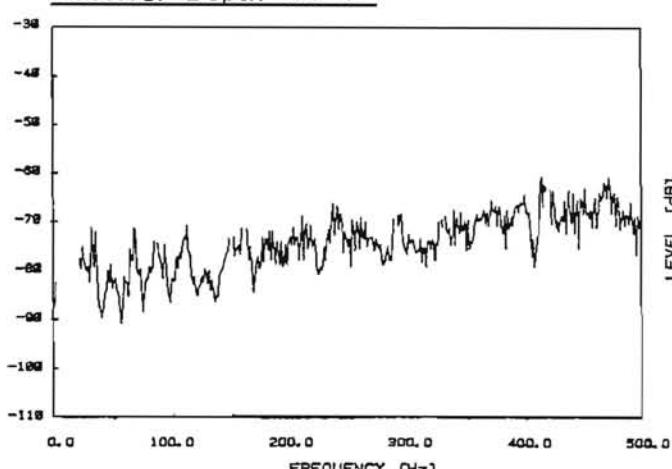
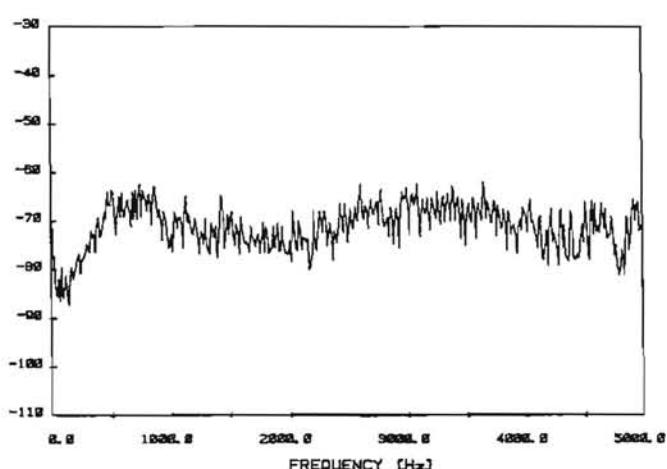
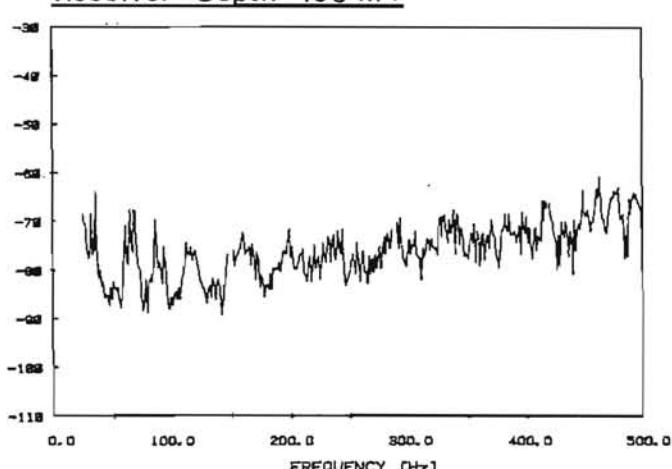
Receiver Depth 5 m :Receiver Depth 50 m :Receiver Depth 100 m :

Figure D.16.

Measured transmission loss in Lancaster Sound, Location B.
Source depth: 4 metres. Water depth : approx. 600 metres.
Distance between source and receiver: 6860 metres (No. 1).



D.21

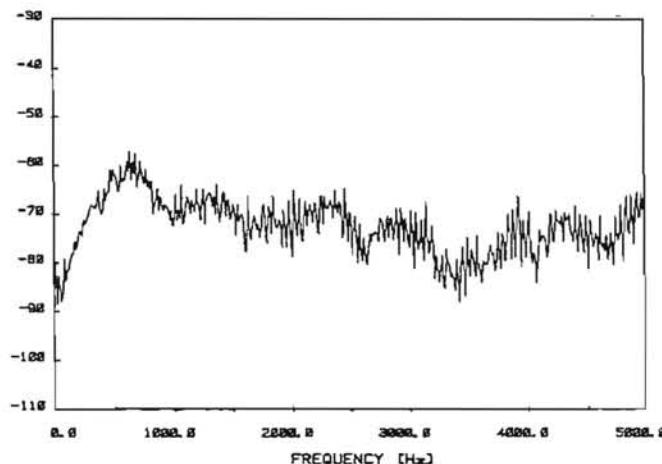
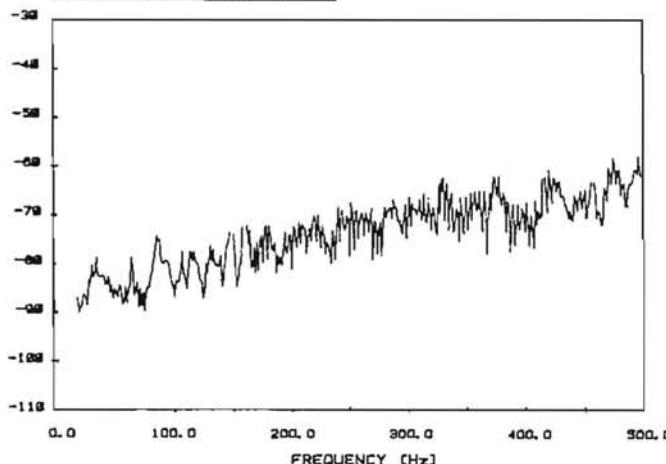
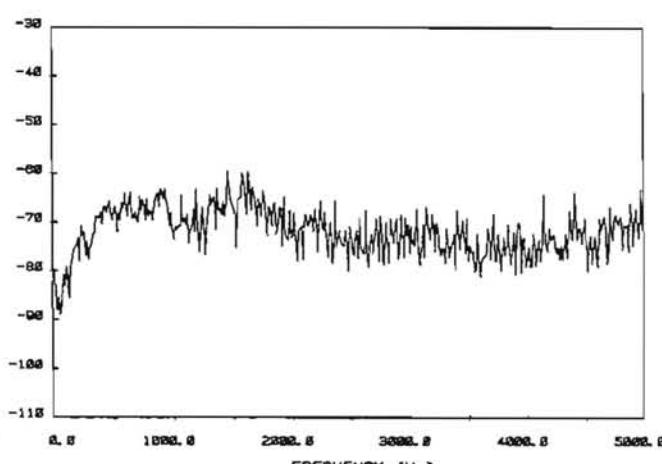
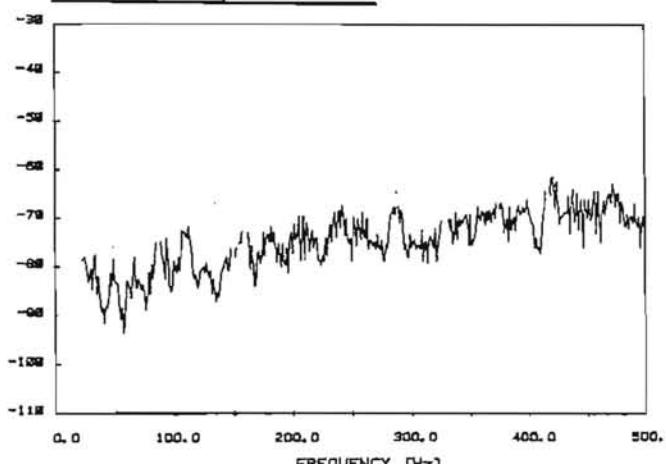
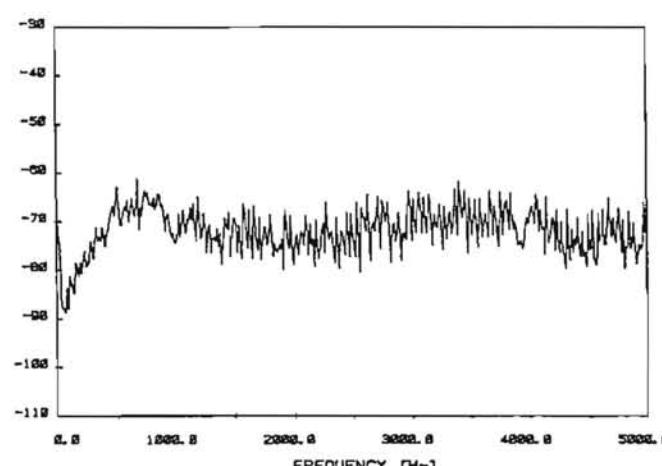
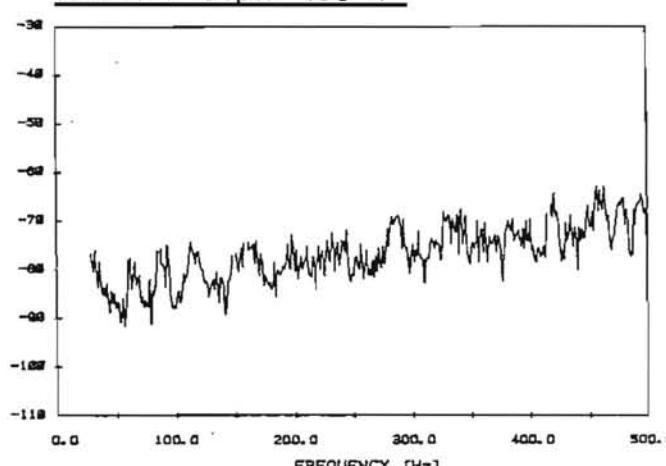
Receiver Depth 5 m :Receiver Depth 50 m :Receiver Depth 100 m :

Figure D.17.

Measured transmission loss in Lancaster Sound, Location B.
Source depth: 4 metres. Water depth : approx. 600 metres.
Distance between source and receiver: 6860 metres (No. 2).



D.22

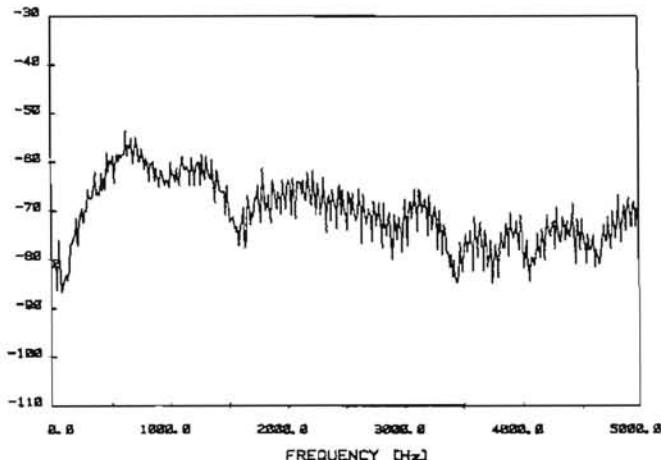
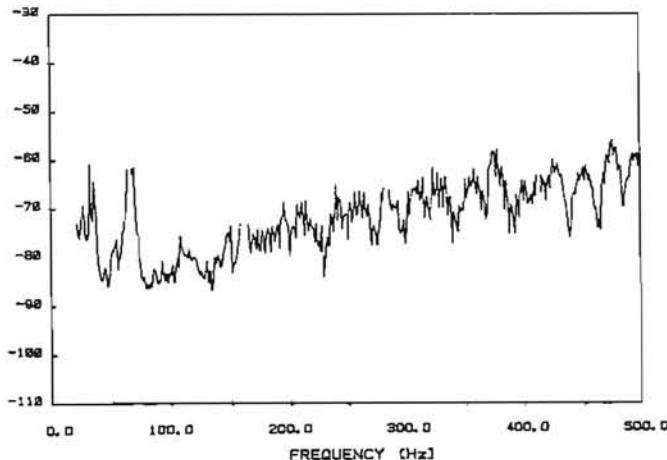
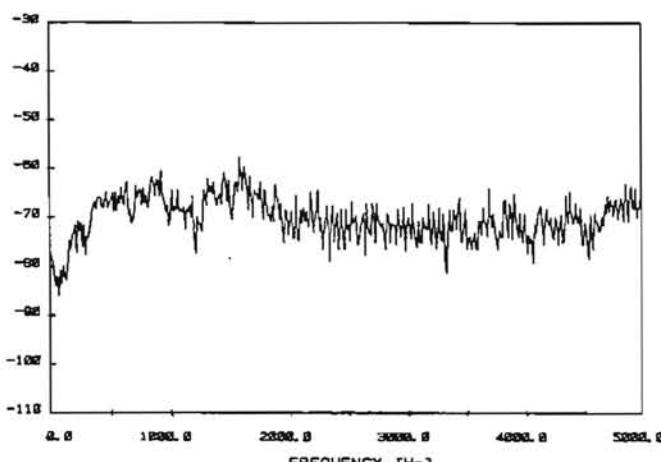
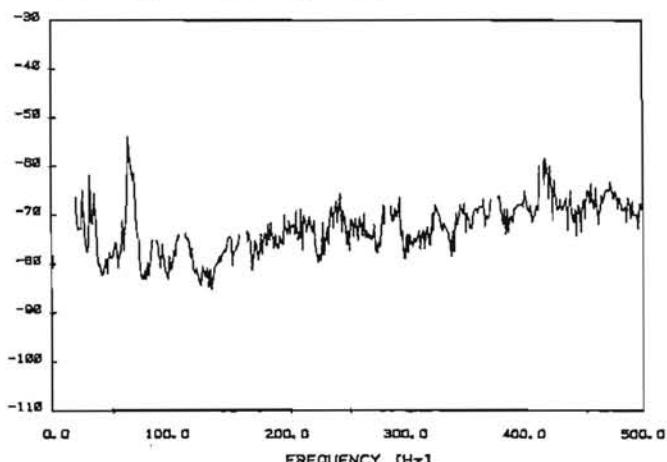
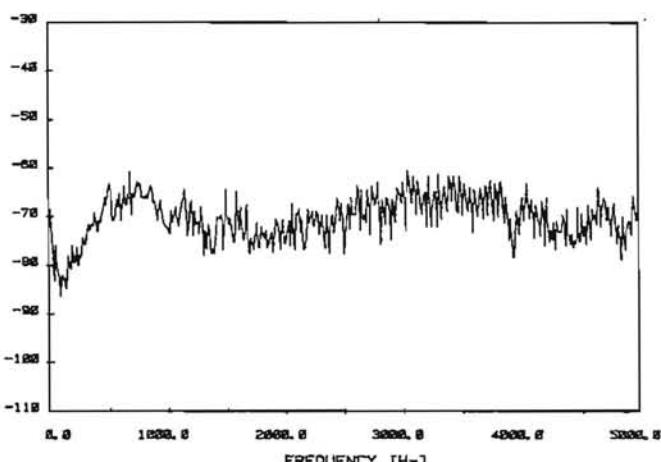
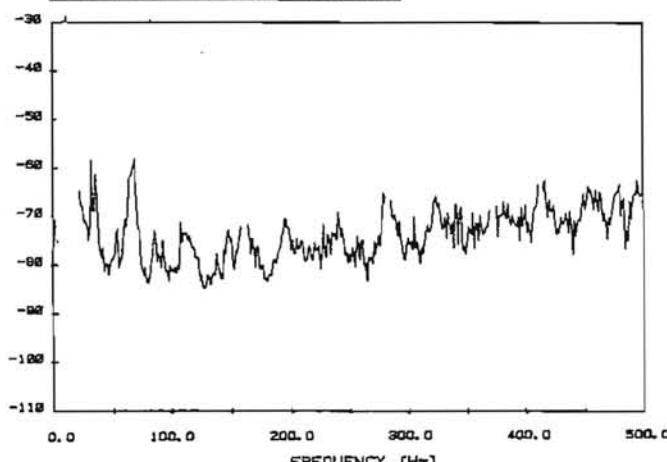
Receiver Depth 5 m :Receiver Depth 50 m :Receiver Depth 100 m :

Figure D.18.

Measured transmission loss in Lancaster Sound, Location B.
Source depth: 4 metres. Water depth : approx. 600 metres.
Distance between source and receiver: 6860 metres (No. 3).



D.23

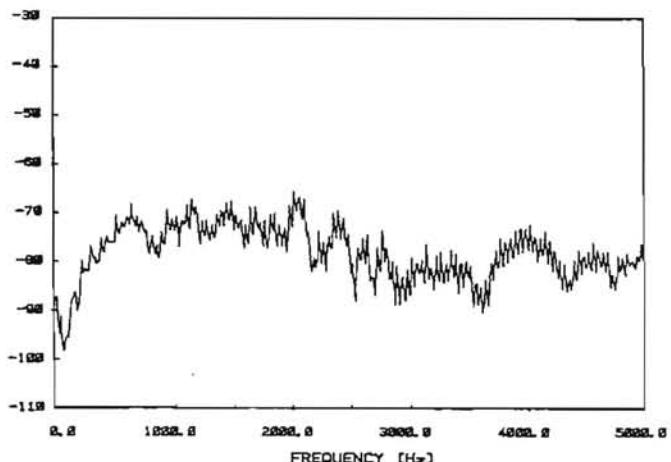
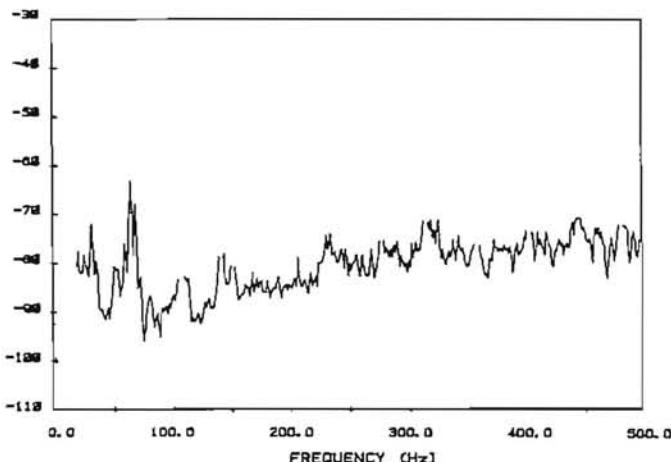
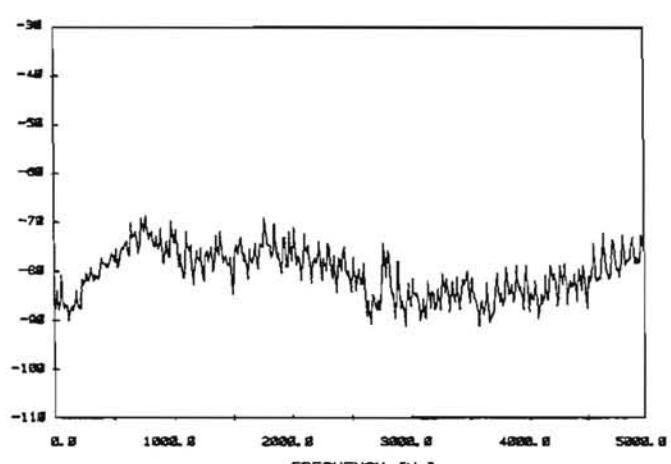
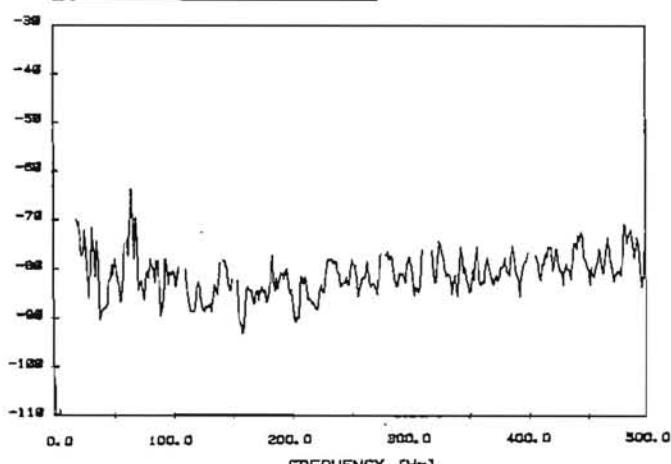
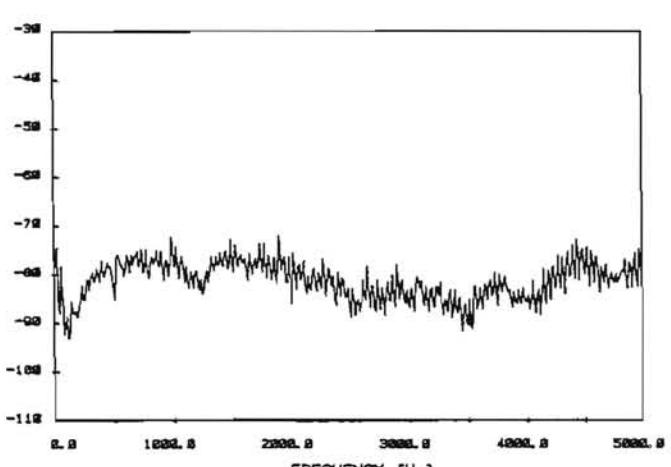
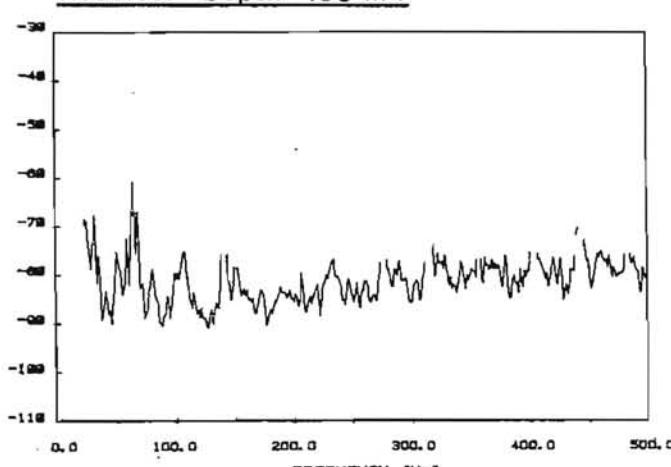
Receiver Depth 5 m :Receiver Depth 50 m :Receiver Depth 100 m :

Figure D.19.

Measured transmission loss in Lancaster Sound, Location B.
Source depth: 4 metres. Water depth : approx. 600 metres.
Distance between source and receiver: 14470 metres (No. 1).



D.24

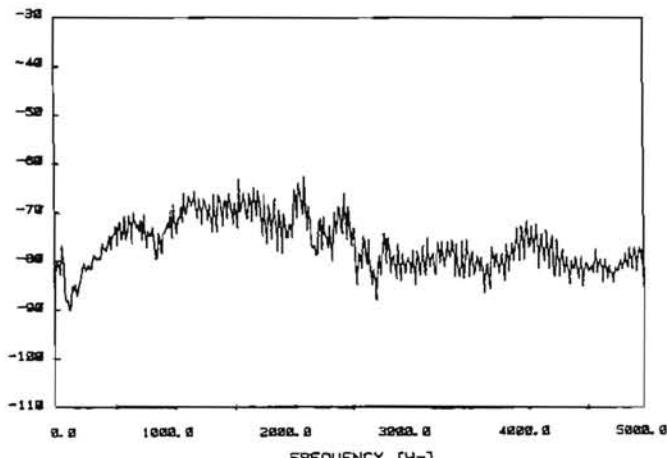
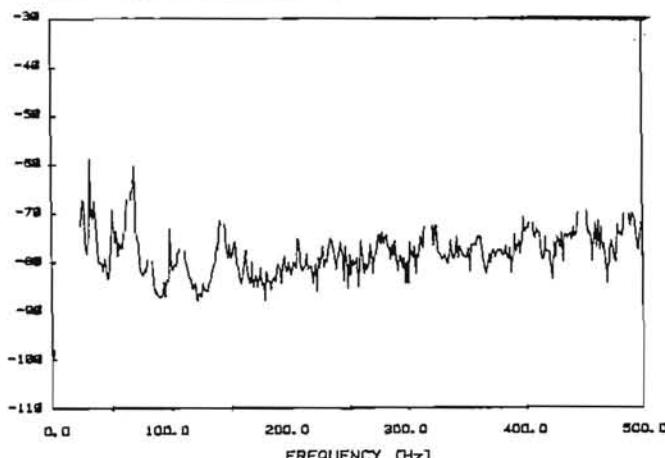
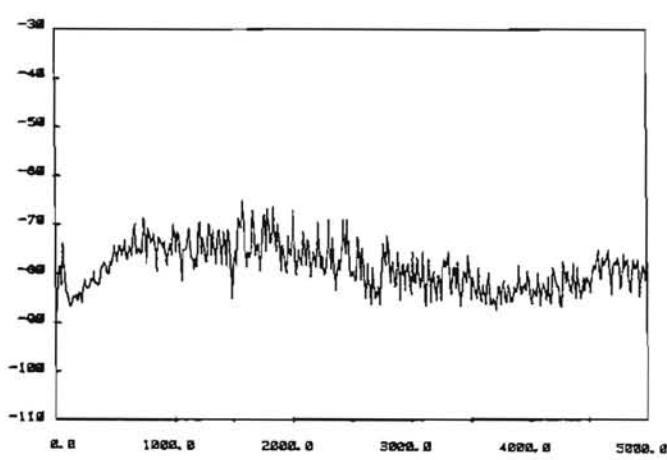
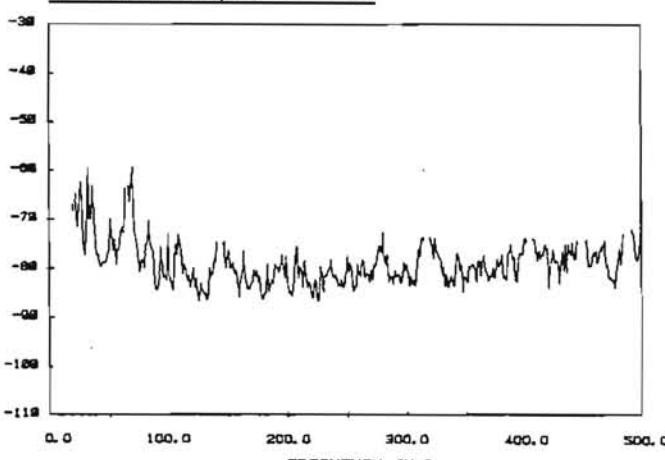
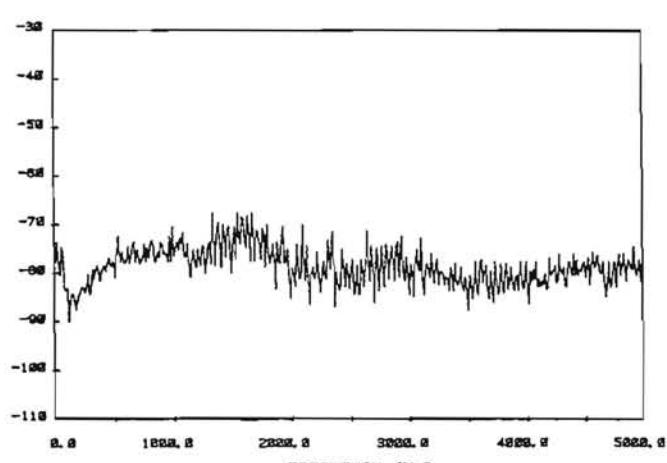
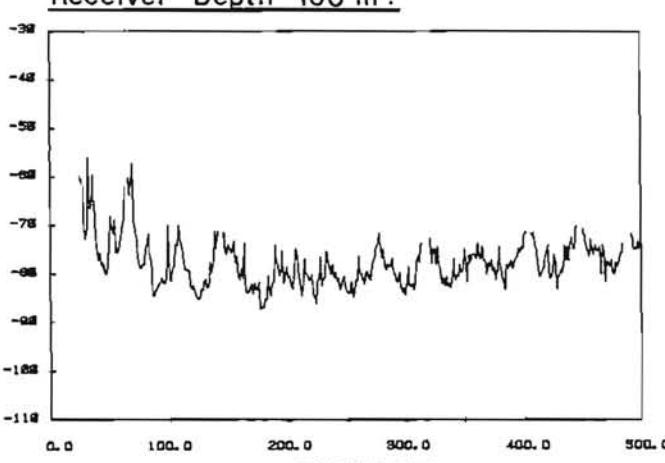
Receiver Depth 5 m :Receiver Depth 50 m :Receiver Depth 100 m :

Figure D.20.

Measured transmission loss in Lancaster Sound, Location B.
Source depth: 4 metres. Water depth : approx. 600 metres.
Distance between source and receiver: 14470 metres (No. 2).



D.25

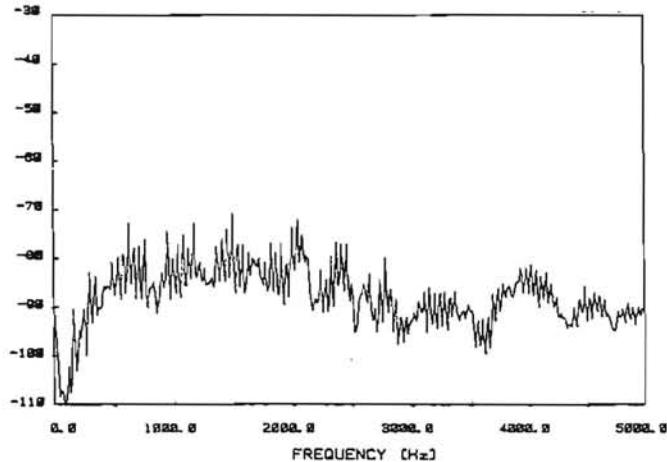
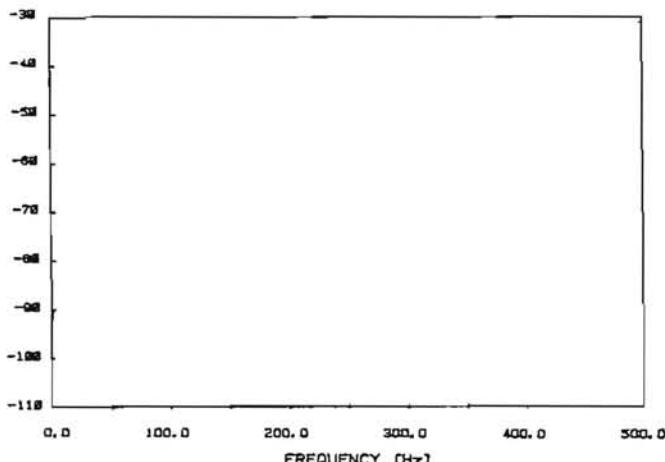
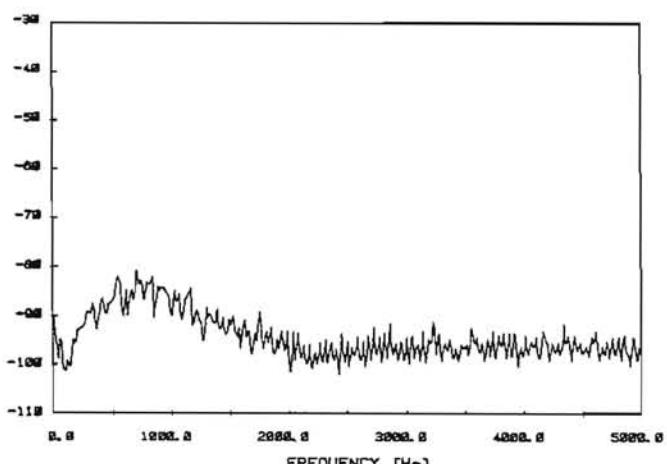
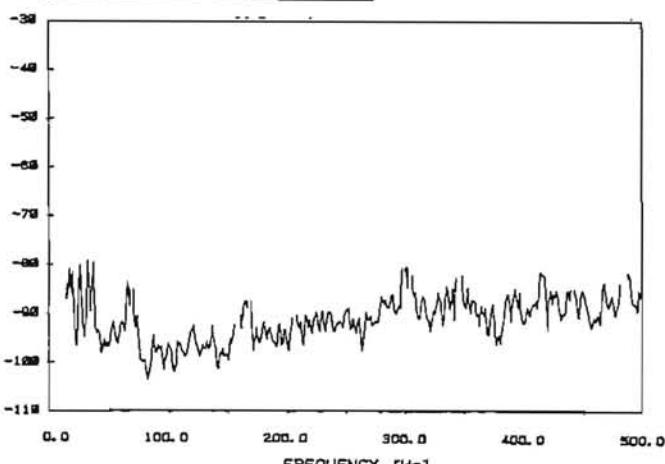
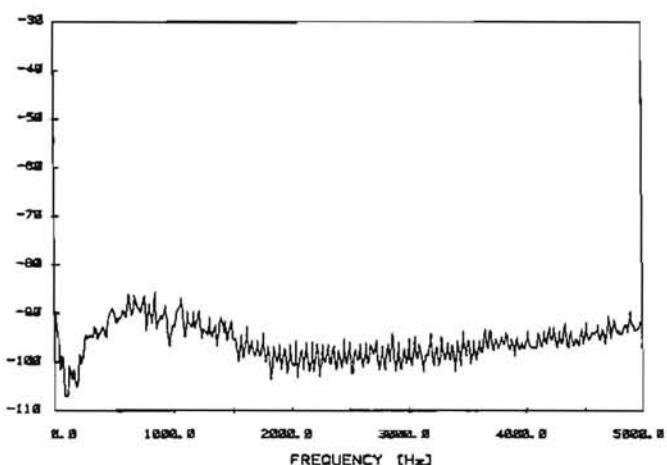
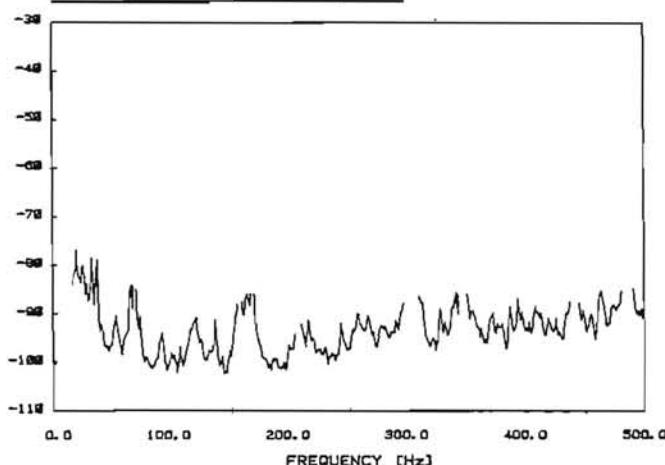
Receiver Depth 5 m :Receiver Depth 50 m :Receiver Depth 100 m :

Figure D.21.

Measured transmission loss in Lancaster Sound, Location B.
Source depth: 4 metres. Water depth: approx. 600 metres.
Distance between source and receiver: 35200 metres (No. 1).



D.26

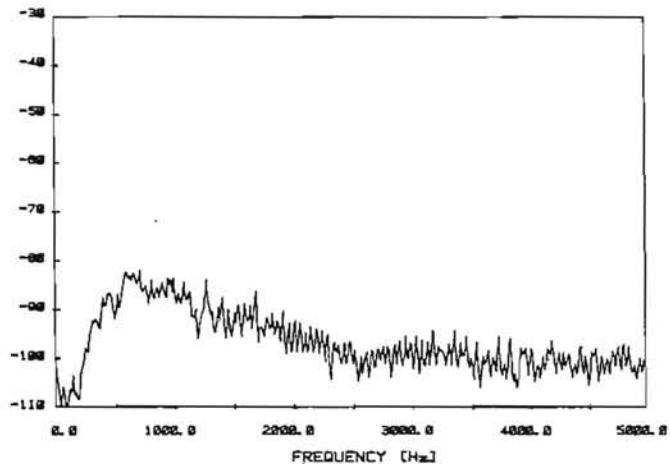
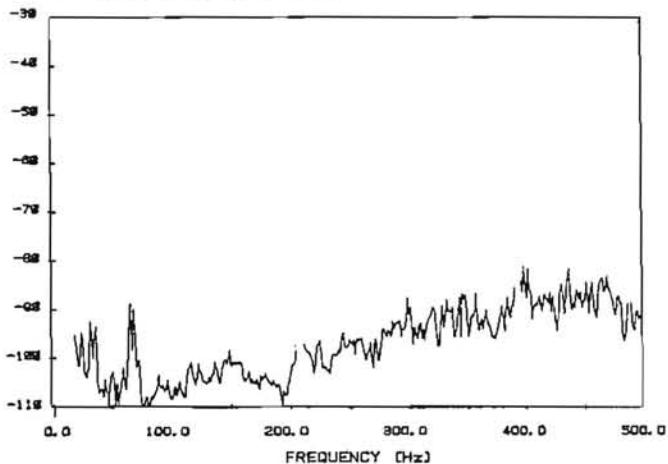
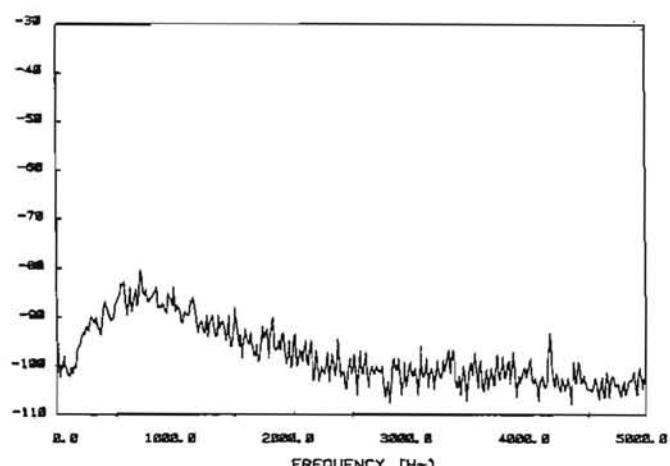
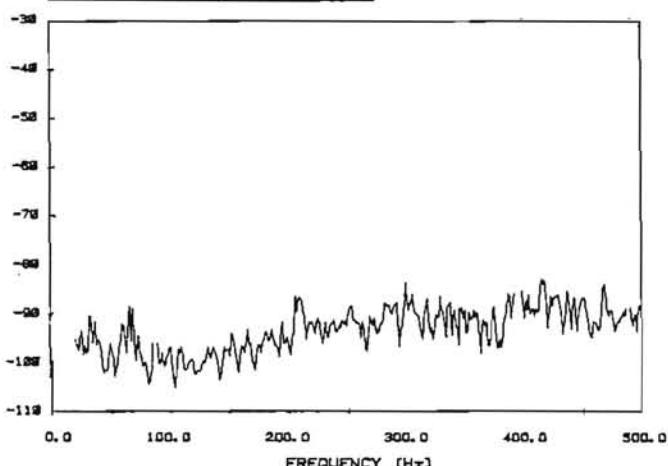
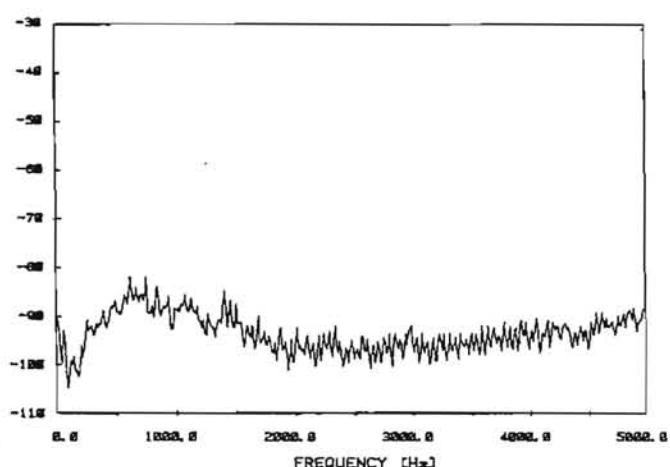
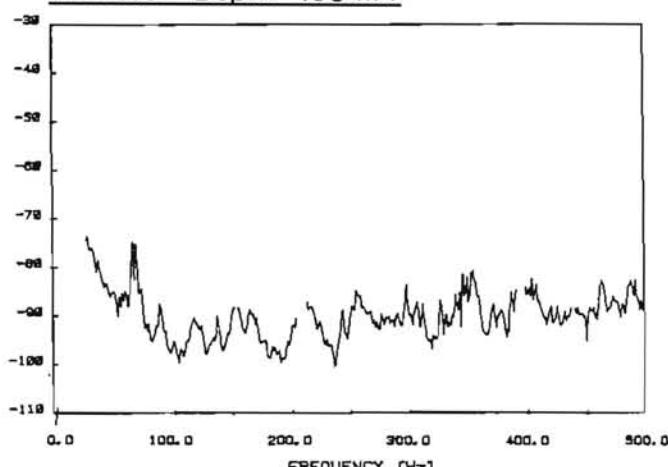
Receiver Depth 5 m :Receiver Depth 50 m :Receiver Depth 100 m :

Figure D.22.

Measured transmission loss in Lancaster Sound, Location B.
Source depth: 4 metres. Water depth: approx. 600 metres.
Distance between source and receiver: 35200 metres (No. 2).

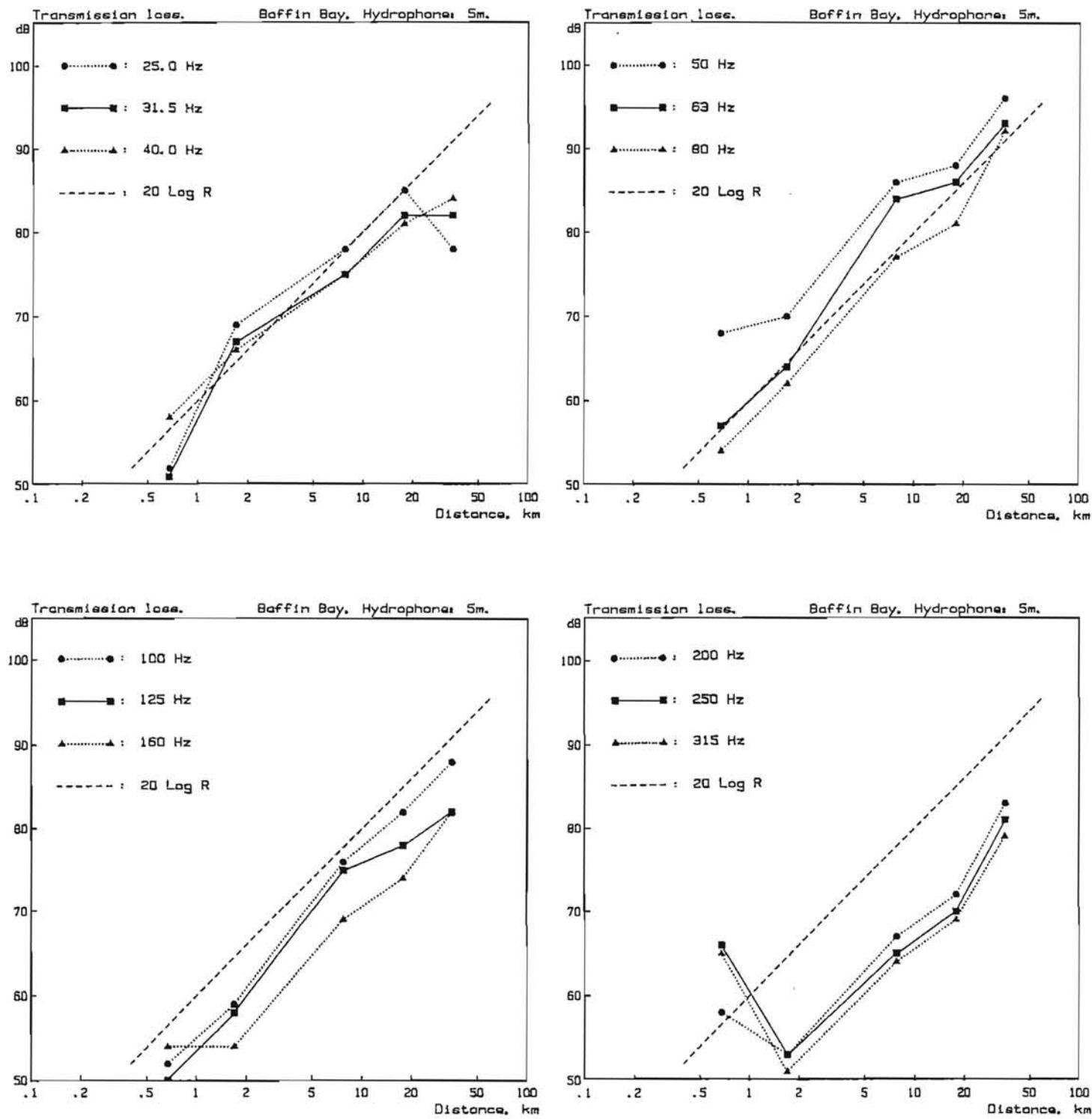


Figure D.23.
Average sound transmission loss in 1/3-octave frequency
bands with centre frequencies 25 Hz to 315 Hz. Baffin
Bay (Location A). Hydrophone depth: 5 metres.



D.28

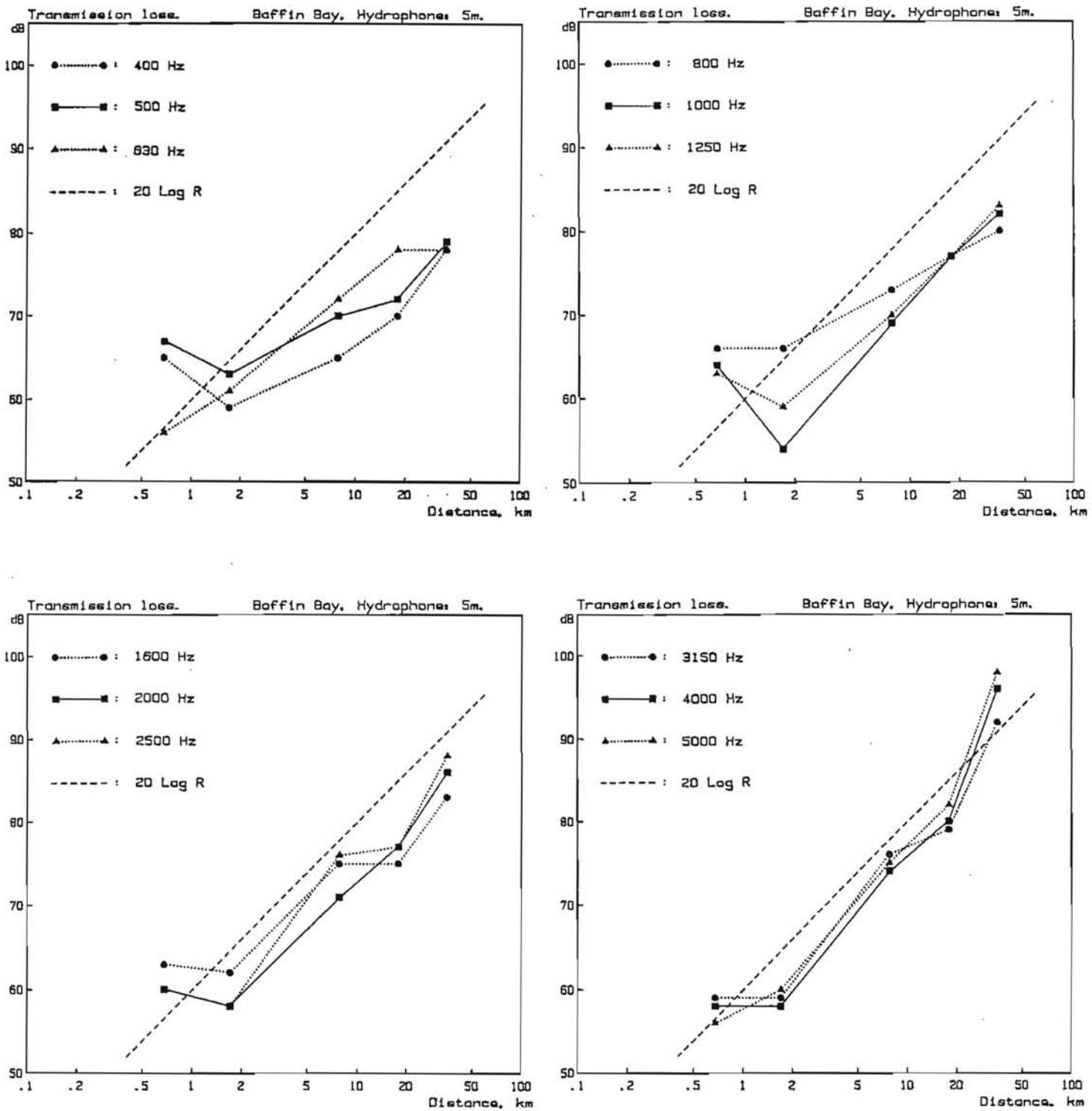


Figure D.24.
Average sound transmission loss in 1/3-octave frequency
bands with centre frequencies 400-5000 Hz. Baffin Bay
(Location A). Hydrophone depth: 5 metres.

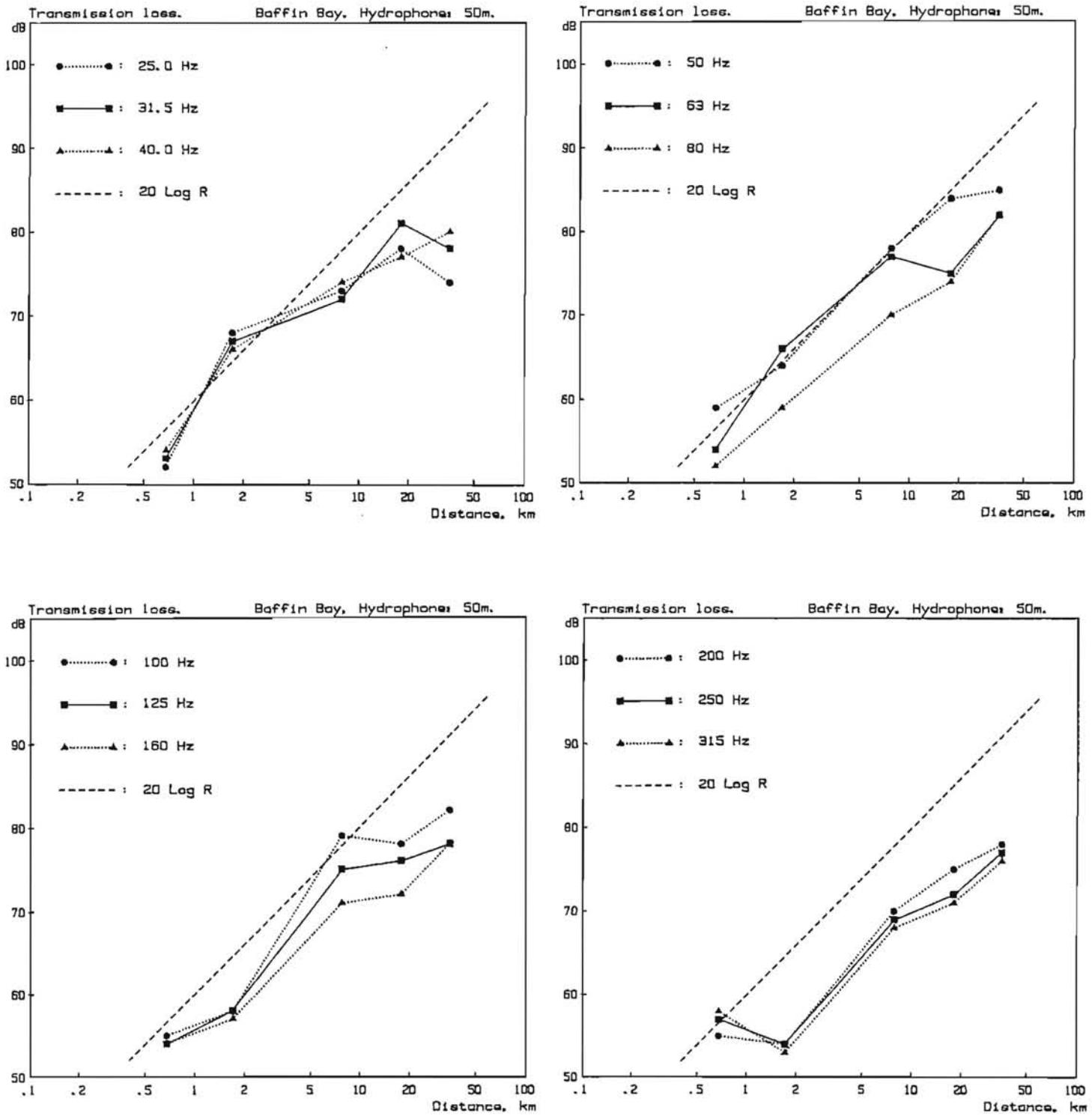


Figure D.25.
Average sound transmission loss in 1/3-octave frequency
bands with centre frequencies 25 Hz to 315 Hz. Baffin
Bay (Location A). Hydrophone depth: 50 metres.

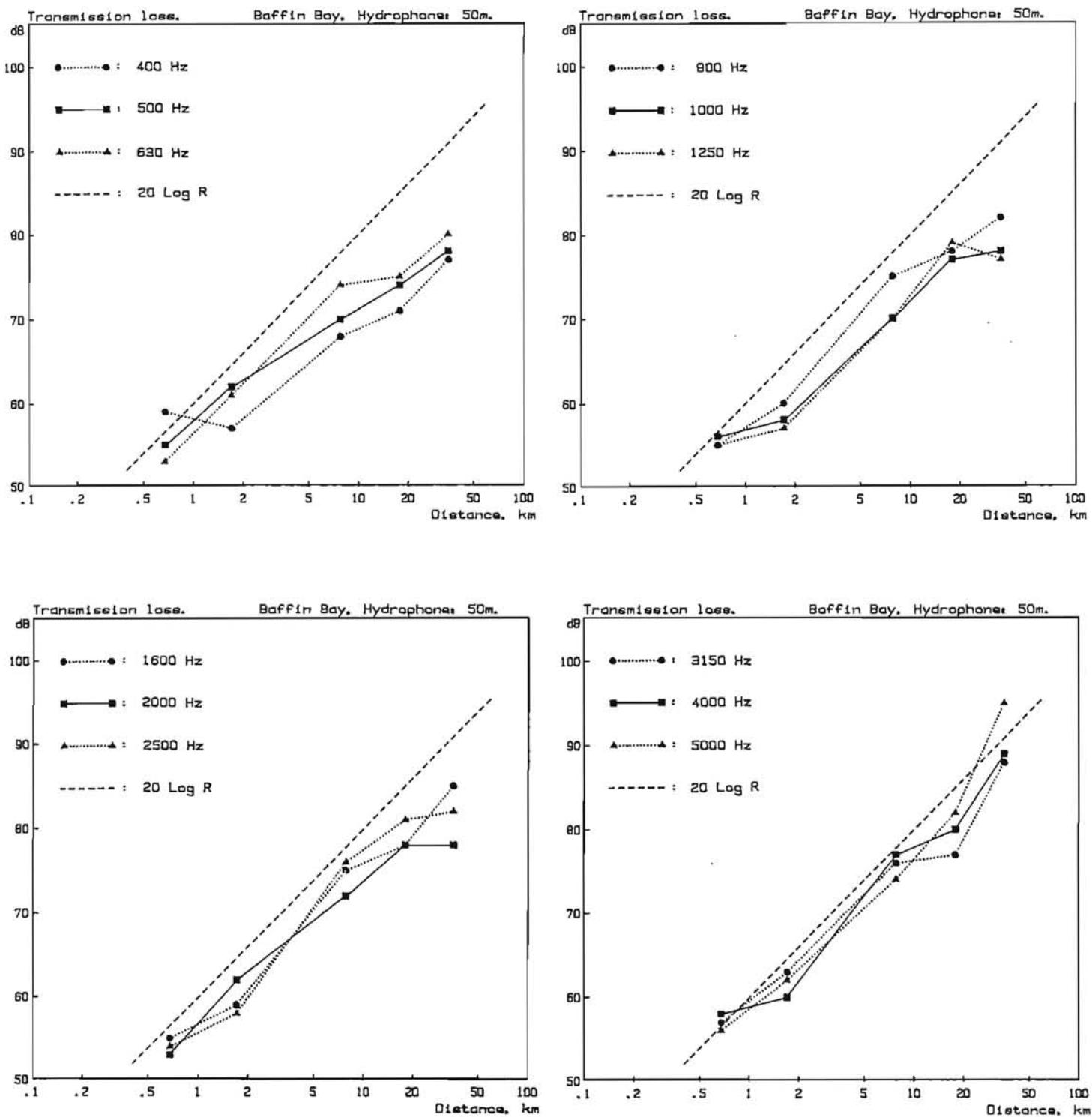


Figure D.26.
Average sound transmission loss in 1/3-octave frequency bands with centre frequencies 400-5000 Hz. Baffin Bay (Location A). Hydrophone depth: 50 metres.



D.31

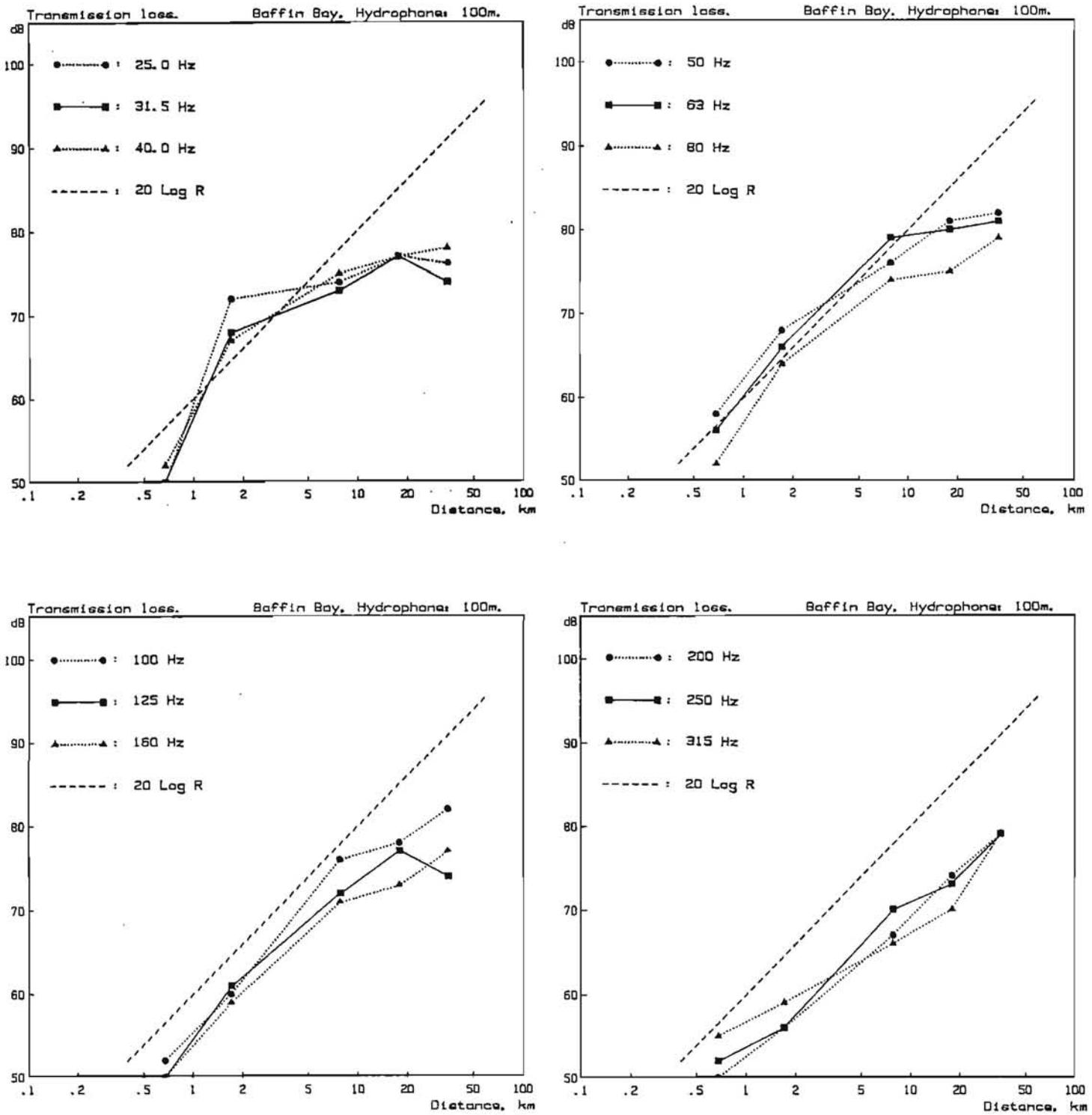
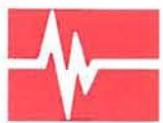


Figure D.27.
Average sound transmission loss in 1/3-octave frequency
bands with centre frequencies 25 Hz to 315 Hz. Baffin
Bay (Location A). Hydrophone depth: 100 metres.



D.32

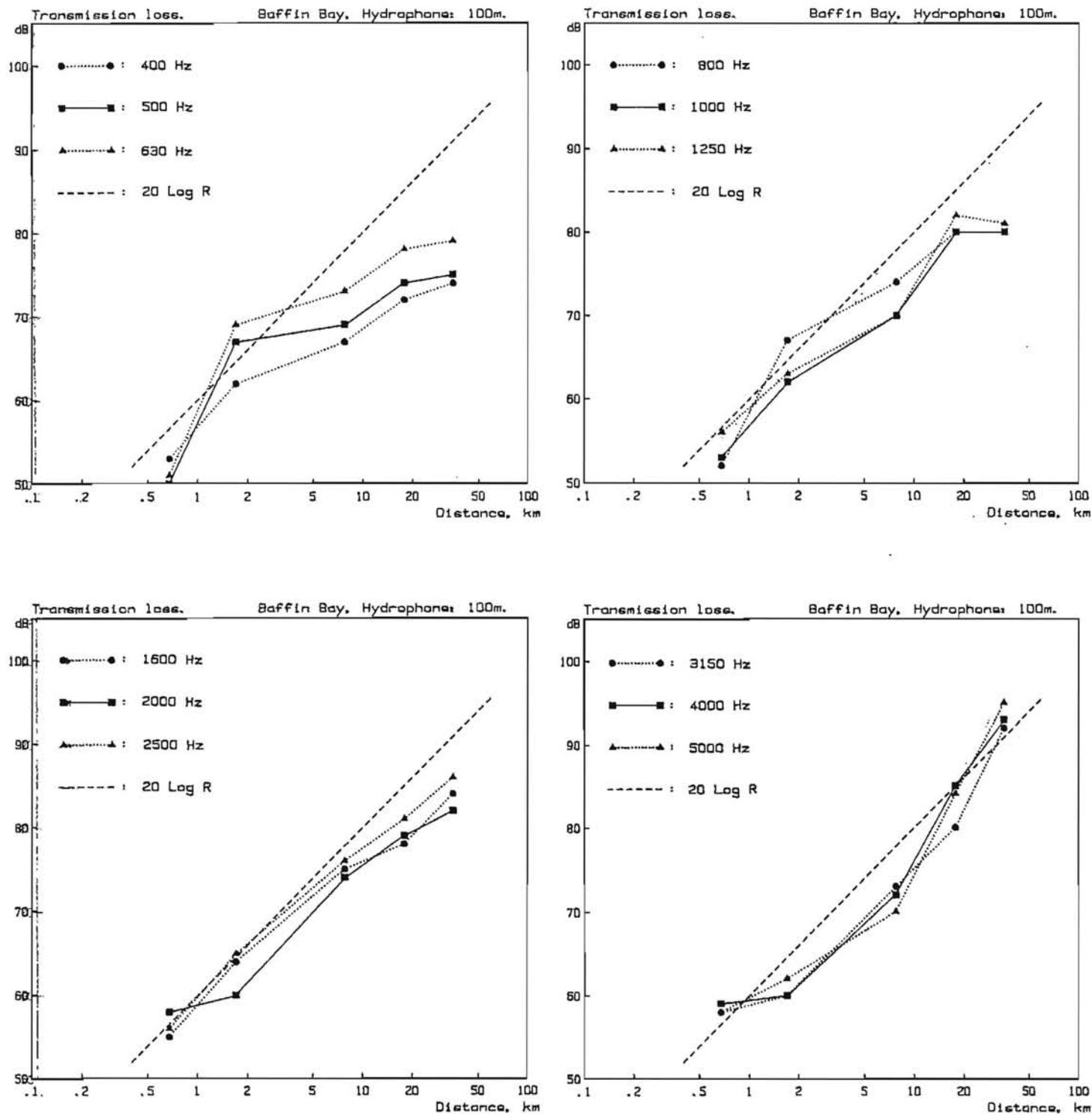


Figure D.28.
Average sound transmission loss in 1/3-octave frequency
bands with centre frequencies 400-5000 Hz. Baffin Bay
(Location A). Hydrophone depth: 100 metres.



D.33

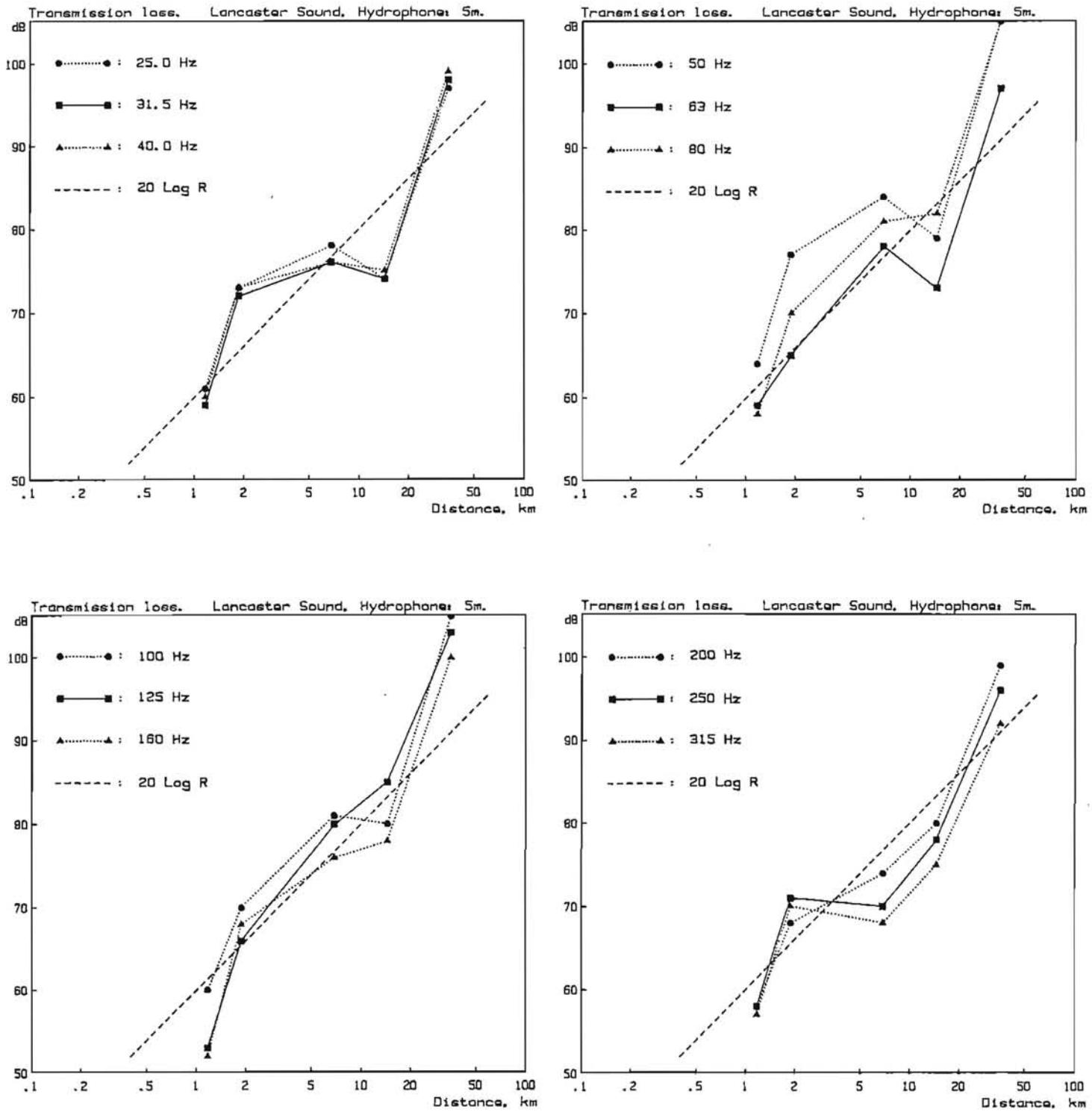


Figure D.29.
Average sound transmission loss in 1/3-octave frequency
bands with centre frequencies 25 Hz to 315 Hz. Lan-
caster Sound (Location B). Hydrophone depth: 5 metres.

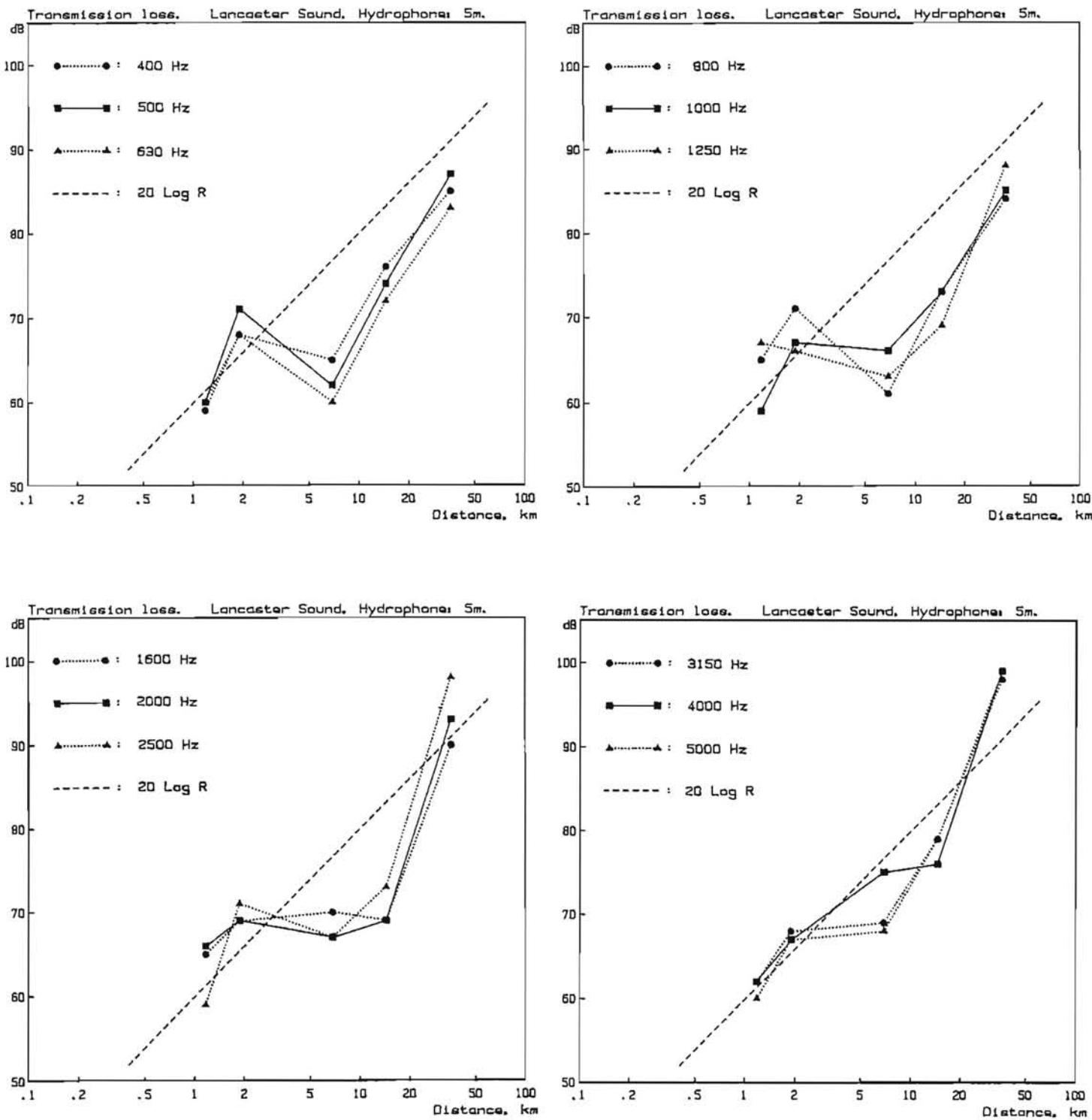


Figure D.30.
Average sound transmission loss in 1/3-octave frequency bands with centre frequencies 400-5000 Hz. Lancaster Sound (Location B). Hydrophone depth: 5 metres.

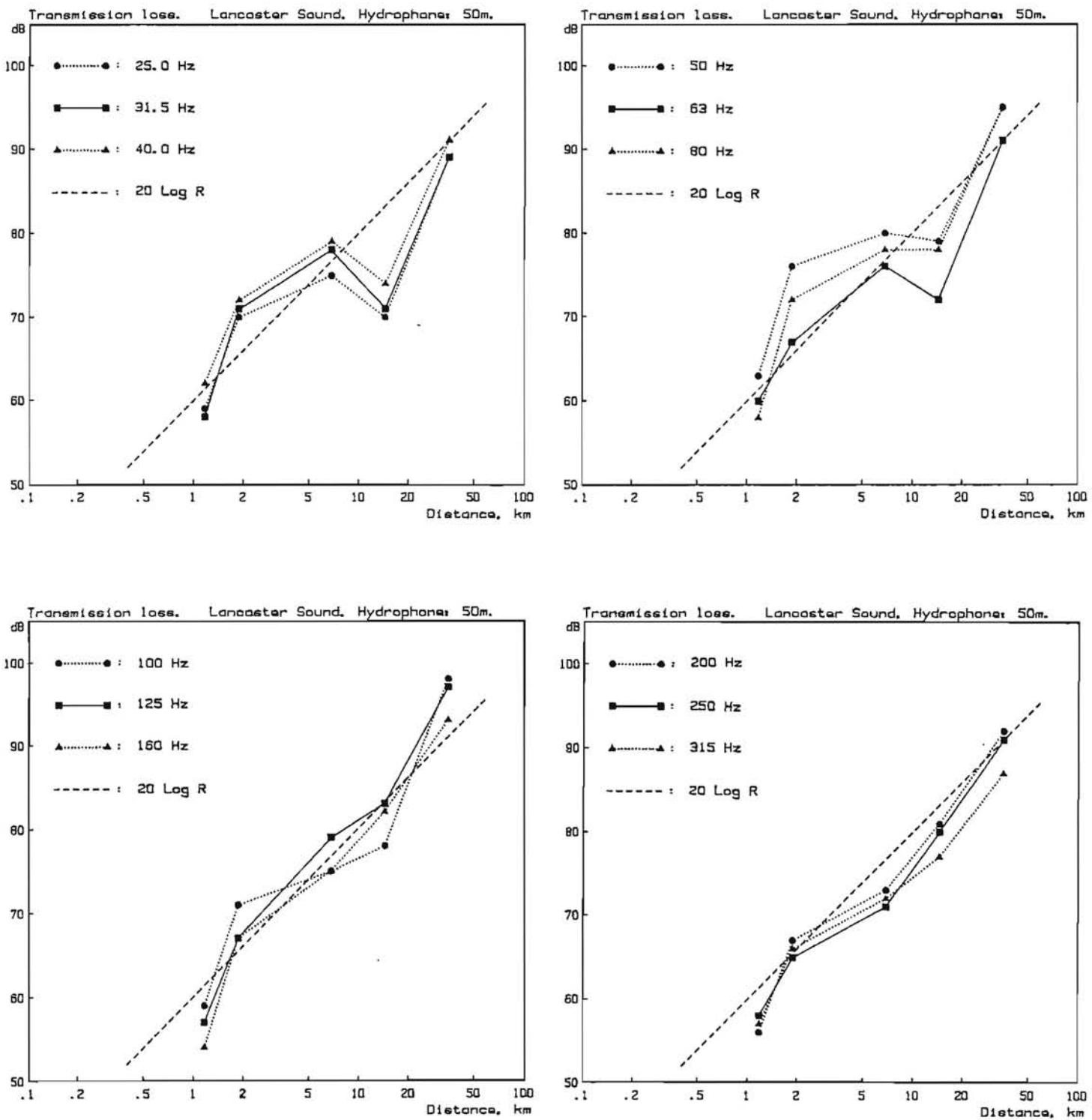


Figure D.31.
Average sound transmission loss in 1/3-octave frequency bands with centre frequencies 25 Hz to 315 Hz. Lancaster Sound (Location B). Hydrophone depth: 50 metres.



D.36

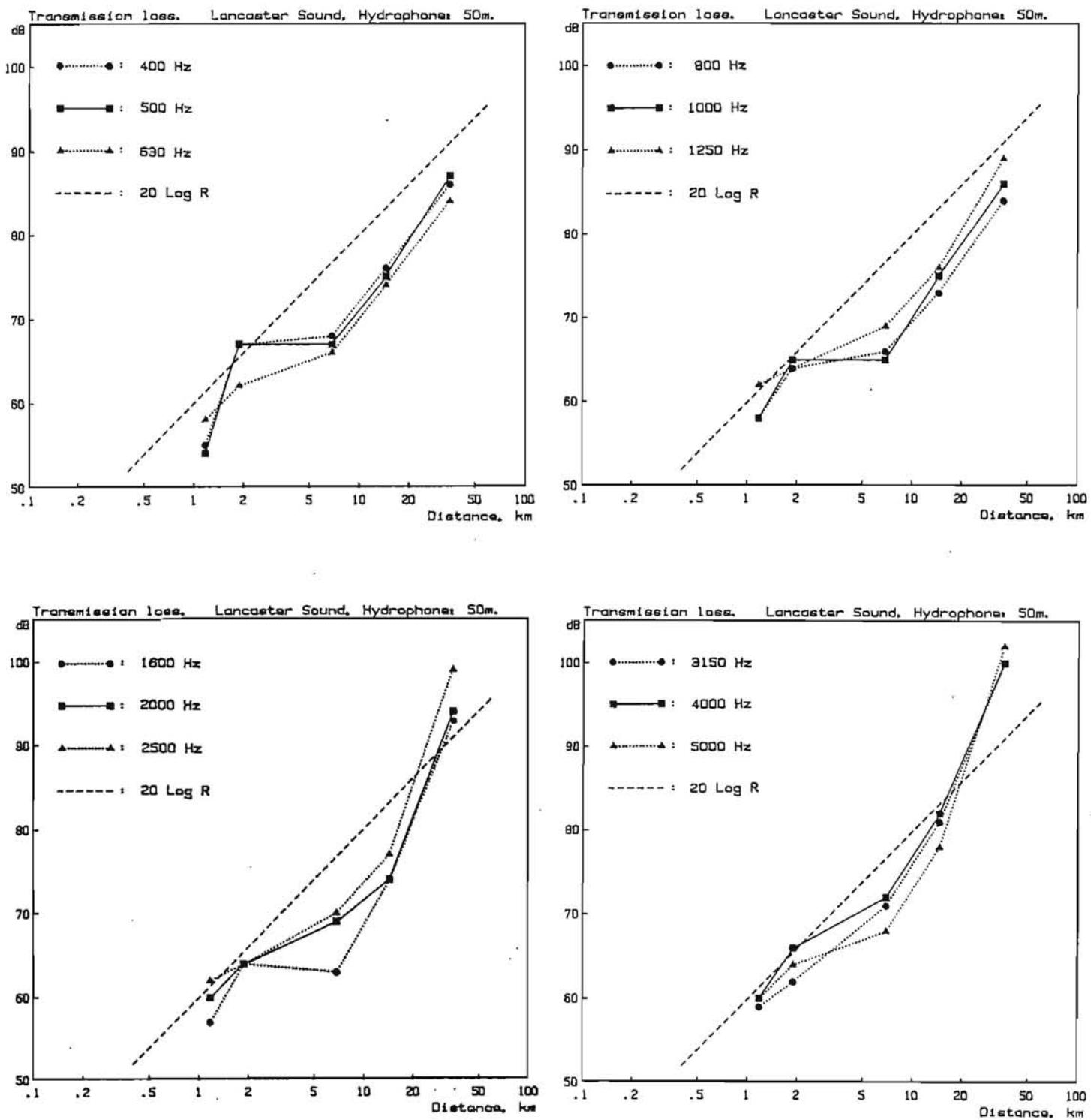


Figure D.32.
Average sound transmission loss in 1/3-octave frequency
bands with centre frequencies 400-5000 Hz. Lancaster
Sound (Location B). Hydrophone depth: 50 metres.

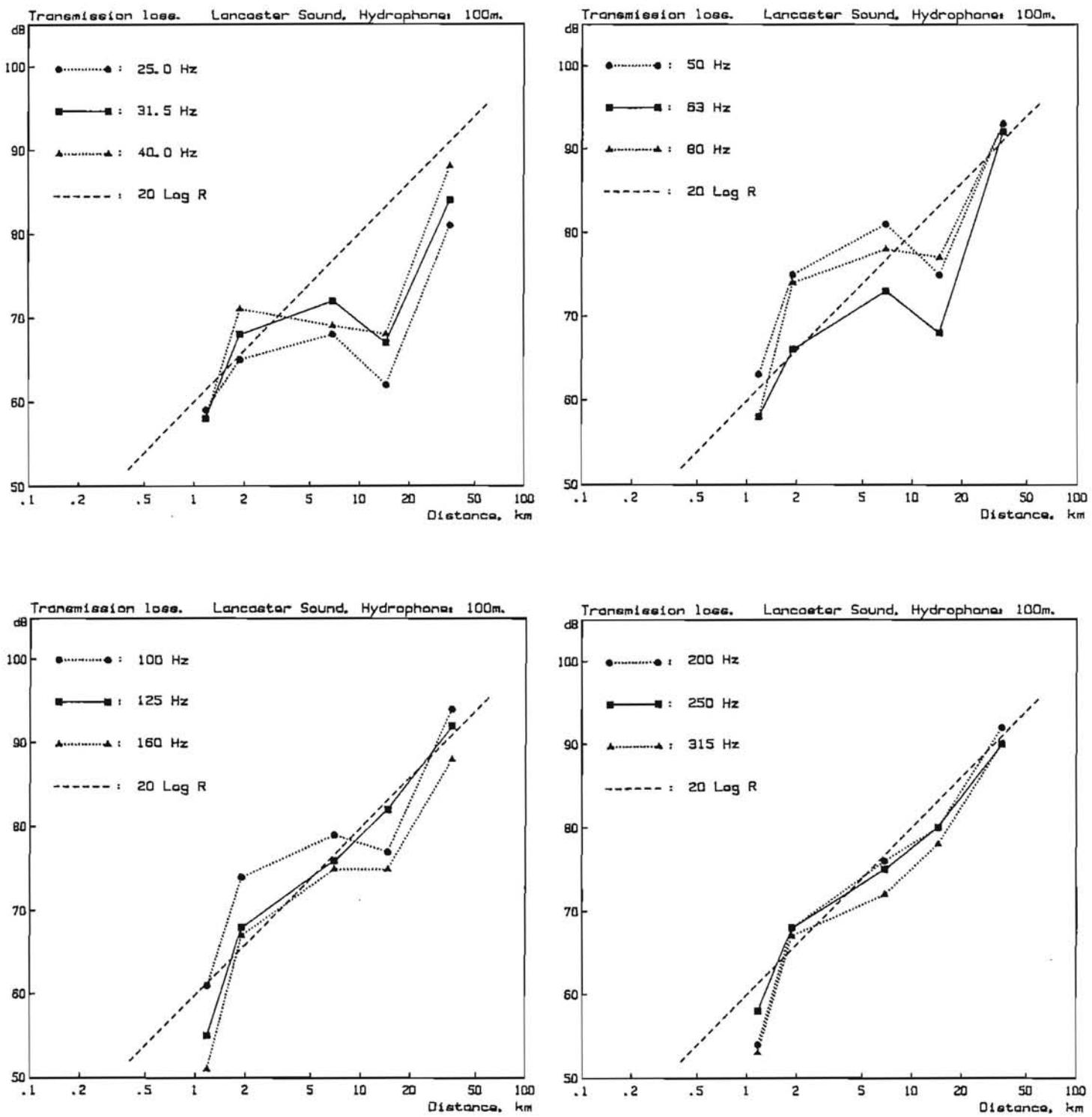


Figure D.33.
Average sound transmission loss in 1/3-octave frequency bands with centre frequencies 25 Hz to 315 Hz. Lancaster Sound (Location B). Hydrophone depth: 100 metres.

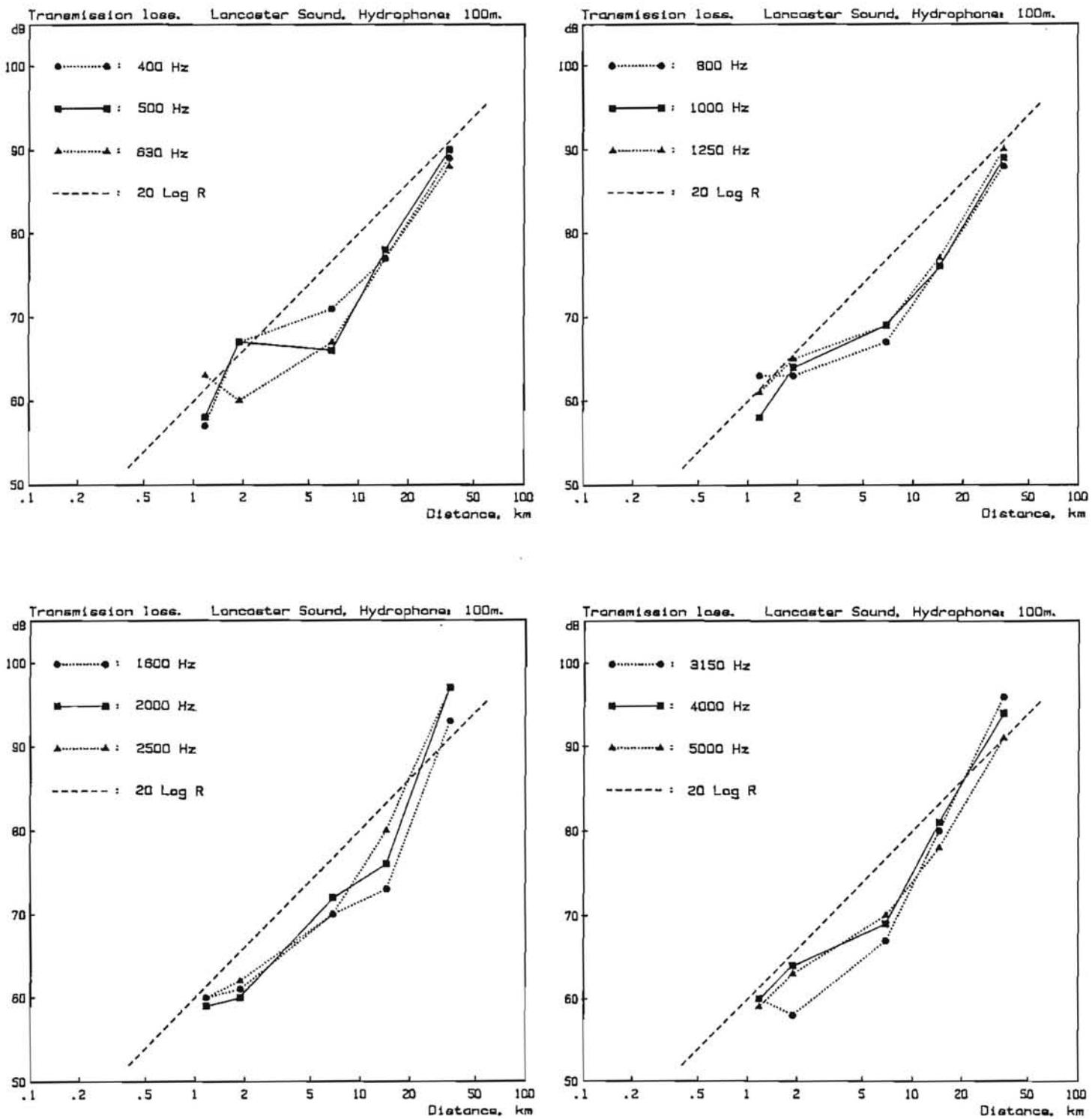


Figure D.34.
Average sound transmission loss in 1/3-octave frequency
bands with centre frequencies 400-5000 Hz. Lancaster
Sound (Location B). Hydrophone depth: 100 metres.

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