Polarforschung 64 (1): 9-17, 1994 (erschienen 1995)

Marine Seismic Profiling in Ice Covered Regions

By Wilfried Jokat[1], Vadim Yu. Buravtsev[2] and Heinz Miller[1]

Summary: We discuss some of the technical problems in carrying out marine-seismic multichannel measurements in ice covered oceans. A streamer noise analysis was carried out during the international expedition ARCTIC'91 in order to derive constraints for seismic measurements in such an environment. These data have been collected under the most severe operational conditions for seismic equipment. The noise analysis as well as the processed data demonstrate that high quality seismic data can be collected in polar regions. Optimum conditions for continous seismic profiling in most severe ice conditions requires a second ice breaker in front of the seismic ship, which itself needs to be an ice breaker.

Zusammenfassung: Technische Probleme, die sich bei der Durchführung von marinen, seismischen Messungen (Mehrkanal) in eisbedeckten Meeresgebieten ergeben, werden diskutiert. Eine Streamer-Noise Analyse, die während der internationalen Expedition ARCTIC'91 durchgeführt wurde, liefert Rahmenbedingungen für seismische Messungen in diesen Meeresgebieten. Diese Daten wurden unter den bisher schwierigsten Bedingungen für das geschleppte seismische Gerät gewonnen. Sowohl die Noise-Analyse als auch die verarbeiteten Daten zeigen, daß es möglich ist, qualitativ hochwertige seismische Daten in den eisbedeckten Polargebieten zu sammeln. Für eine kontinuierliche Meßfahrt unter schwierigsten Eisbedingungen ist allerdings ein zweiter Eisbrecher notwendig, der dem „Seismik-Schiff" (ebenfalls ein Eisbrecher) vorausfährt.

INTRODUCTION

Geophysical research in the Polar regions is a difficult task. Due to the permanent sea ice coverage, scientific knowledge about these areas is growing very slowly. This is especially valid for geophysical and geological information which require an ocean-going platform. The potential fields can be measured using satellite and airborne methods and in spite of the remoteness and the extreme climate of the polar regions, the potential fields are the best known geophysical parameters in the Arctic and Antarctic. Due to the high logistic expenditure for seismic investigations, there are only a few seismic lines existing onshore in the Antarctic. The situation is different for marine seismic investigations. As the sea ice coverage is highly variable, it is possible to carry out marine geophysical experiments in areas partially covered by sea ice (Fig. 1a). There are, however, large parts of the polar oceans, which are permanently covered by sea ice. In Antarctica these are mainly the shelf areas of the continental margins. Thus, the main interpretations of Antarctic continental geology have been derived from the 2 % of ice free areas on the continent.

The situation in the Arctic (North of 80°) is different. The Arctic Ocean consists of several basins with water depths ranging from 1000 to 4000 m. In the past, most of the geophysical research in the Arctic Ocean was carried out from ice islands as logistical platforms that drift with the current systems. Most of the reflection and refraction data (HALL 1970, MAIR & FORSYTH 1982, JACKSON et al. 1982, DURCKWORTH & BAGGEROER 1985, KRISTOFFERSEN & HUSEBYE 1985, FORSYTH et al. 1986, for an overview see JACKSON et al. 1990, GRANTZ & MAY 1992) were collected in this way, and models of the Arctic basin geology have been mainly derived from these results. Additionally, marine single channel data were collected from ice breaking ships (JACKSON et al. 1990). There are about 4000 km of seismic reflection data in the Amerasian Basin and 1700 km in the Eurasian Basin before 1991. Using this information together with other geophysical data, such as airborne geophysics and seismology, the gross geological structure and history of the Arctic Ocean has been derived. But details such as sediment thickness, stratigraphy or crustal thickness are only known at isolated spots.

In this paper we highlight some of the technical problems in carrying out seismic reflection surveys in heavy sea ice with conventional research ice breakers. We will mainly use results collected during an international multi-ship expedition ARCTIC'91 in the Arctic Ocean (FÜTTERER 1992, ANDERSON & CARLSON-LONNROTH 1991). Here, the combined operation of the Swedish ice breaker *Oden* and the German ice breaking research vessel *Polarstern* resulted in a breakthrough in collecting geophysical data in this hostile environment. In total, 1500 km of multichannel seismic data (3-12 fold) was collected in the Eurasian Basin (Fig. 1b), using a 500 m streamer (300 m active length, 12 channels) and a 24 ltr airgun array. Almost 300 km of this data set was measured with *Polarstern* only (single ship operation) at 88° N, 161° E (JOKAT et al. 1992b). The seismic data set represents nearly the same line length that has been previously shot in the decades before in the Eurasia Basin. We will present a noise analysis and one data example. A more detailed presentation of the geophysical results can be found in two papers by JOKAT et al. (in press).

[1] Dr. Wilfried Jokat, Prof. Dr. Heinz Miller, Alfred Wegener Institute for Polar and Marine Research, Columbusstrasse, D-27515 Bremerhaven, Germany.

[2] Dr. Vadim Buravtsev, NIIMorgeophysica, Karl Marx Street 19, Murmansk 183048, Russia.

Manuscript received 03 May 1994; accepted 23 November 1994.

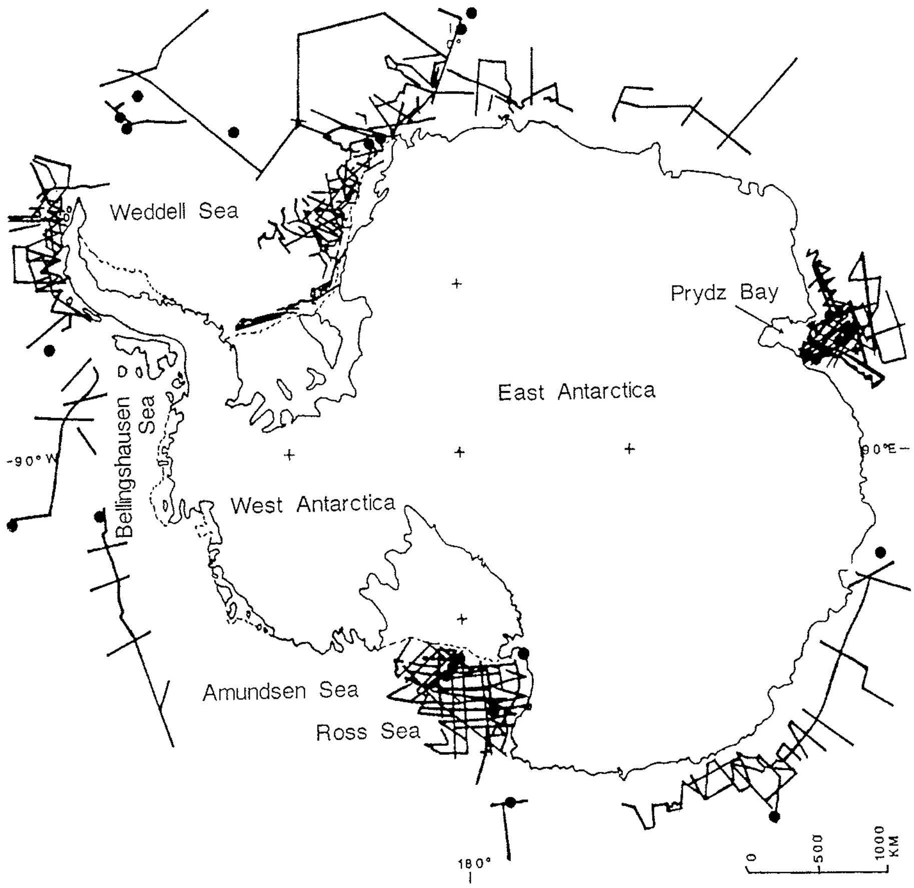


Fig. 1a: Location map of marine multichannel seismic reflection profiles collected between 1976 and 1988 in the Antarctic. Bold dots indicate locations of ODP and DSDP drill holes; participating countries and institutions: USA., USGS; Australia, BMR.; Brazil, Petrobras; France, IFP; Germany, BGR and AWI; Italy, OGS; Japan, JNOC; Norway, NARE; Poland, PAS; United Kingdom, BAS; U.S.S.R., SAE; from BEHRENDT (1990).

Abb. 1a: Lageplan der reflexionsseismischen Profile (Mehrkanal), die zwischen 1976 und 1988 in der Antarktis gemessen wurden. Die Punkte markieren ODP- und DSDP-Bohrlochlokationen; aus BEHRENDT (1990).

ICE CONDITIONS

Most of the measurements made during the ARCTIC'91 cruise (JOKAT et al. 1992a) were carried out in 7-9/10 ice coverage. The sea ice consisted of ice floes with varying size (500 to 5000 m in diameter, ULANDER et al. 1991) and thicknesses ranging from 1-2.5 m with leads of open water in between (Fig. 2, Tab. 1). The general technique for the ship's progress was therefore to follow these leads or cracks. To allow more or less continuous progress of the ship it was necessary to speed up in open waters as often as possible. The maximum speed was eight knots. Passing ridges between floes reduced the speed to below 2-3 knots, and the ship moved very slowly even under full power. In most cases it was possible to break through the ice ridge after several minutes of pushing the floe. If not, it was necessary to retrieve the geophysical equipment, before the ship could move back off in the freshly cut channel to gather momentum for a new ramming. For the few lines we shoot with a single ship only it was therefore essential to optimize the ship's track in order to allow continuous operation, instead of optimizing the seismic measurements concerning noise level and ship's track. Conditions became much better when a second icebreaker (*Oden*) sailed ahead of the seismic survey vessel (*RV Polarstern*). Although the track was still a crooked line, the noise level was now lowered considerably. Unfortunately, extensive helicopter reconnaissance flights for supporting the ship's navigation in the ice were not possible due to rapidly changing visibility.

Fig. 2: Picture showing the ice breaking research vessel *Polarstern* operating in pack ice during the cruise in the Central Arctic in 1991. The ship uses open leads and cracks between the floes to make progress.

Abb. 2: Forschungsschiff *Polarstern* während der Messungen in der zentralen Arktis (1991). Beim Meßbetrieb im dichten Packeis müssen möglichst Bereiche offenen Wassers und Risse zwischen den Eisschollen genutzt werden.

OPERATION OF TOWED EQUIPMENT

In conventional seismic experiments long linear airgun arrays are towed several tens of meters behind the seismic vessel. In heavy ice conditions this setup is not possible. The channel of open water produced by the icebreaker is closed by sea ice within 50 m behind the vessel. Thus, the likelihood of

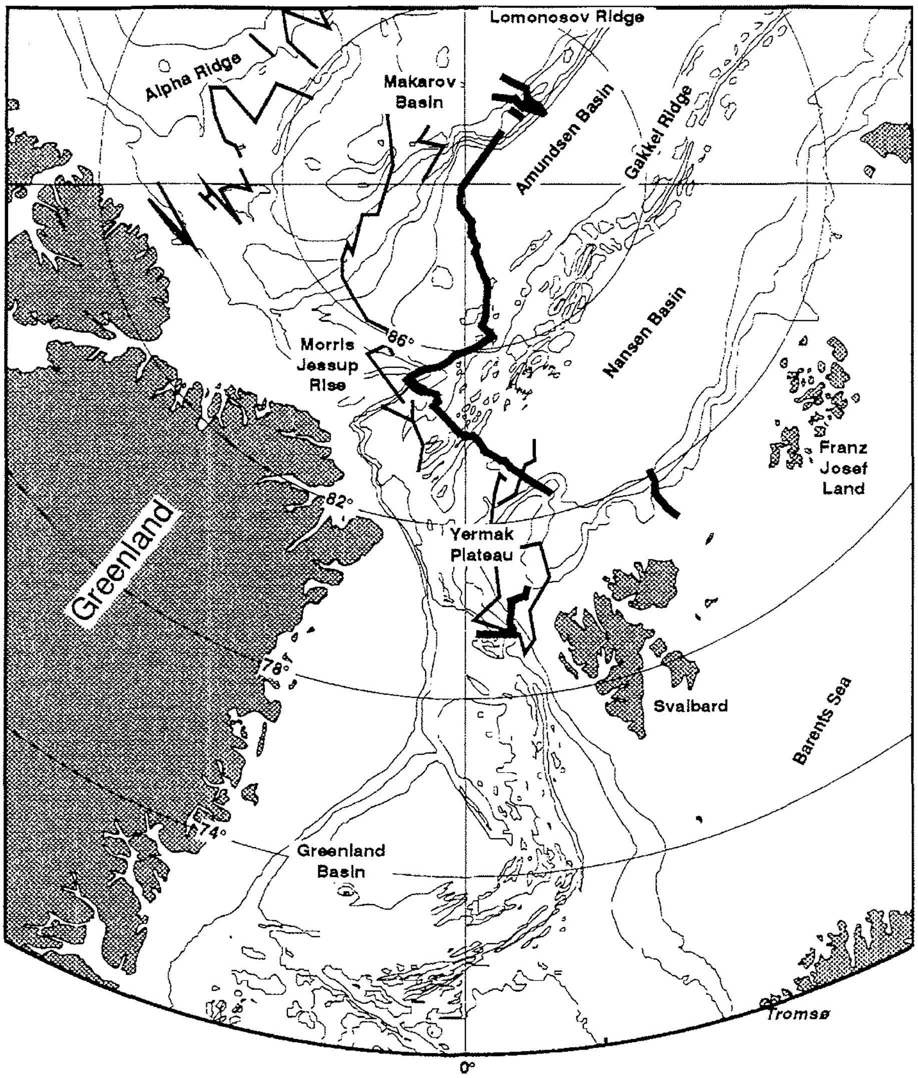


Fig. 1b: Location of single and multichannel seismic reflection profiles (Arctic) in the Eurasian and parts of the Amerasian Basin. Thin lines are shot from icelands and single ice breakers before 1991. Bold lines represent the profiles shot during the ARCTIC'91 cruise.

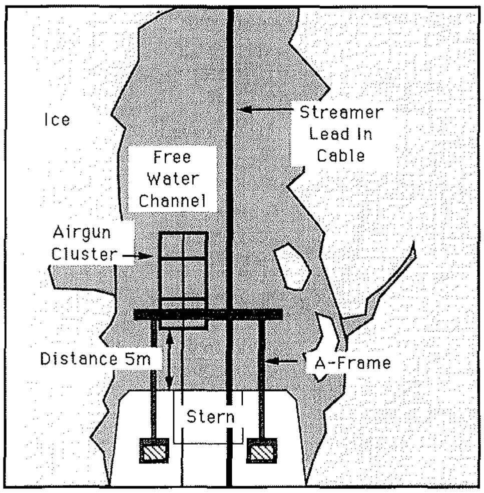
Abb. 1b: Lageplan von seismischen Ein- und Mehrkanal-Daten (Arktis), die im eurasischen und Teilen des amerasischen Ozeans vermessen wurden. Die dünneren Linien markieren die Profile vor 1991, die von Eisinseln oder einzelnen Eisbrechern gesammelt wurden. Die fetten Linien kennzeichnen Profile, die im Rahmen von ARCTIC'91 aufgenommen wurden.

damaging supply cables is very high. In a two ship operation with ice breaker *Oden* ahead, we used an airgun cluster of eight PRAKLA-SEISMOS airguns (3 l each) with a total volume of 24 l mounted on a frame. The frame was towed approximately 5 m behind the ship's stern to reduce damages through drifting ice floes (Fig. 3).

The main damage to the 24 l airgun cluster occurred to the pressure hoses on the frame itself. The supply cables between the ship and the frame were protected by a 10 mm thick rubber hose (10 cm in diameter) and were not damaged at all. The cables on the frame were strained due to ice floes drifting over the frame during low speeds of the ship. Only minor damage arose from large ice floes rising behind the ship, because the frame was towed close to the stern.

The most critical situations for loosing the airgun frame occurred during strong variations in the ship's speed accompanied with sharp changes in the ship's track. We had only minor problems with freezing of the airguns in the water where temperatures were between 0° and -1° C. For colder temperatures (T < -1° C), especially in regions where new ice was formed, we had a significantly higher degree of airgun malfunction due to freezing.

Accurate velocity determinations in seismic reflection experiments strongly depend on the maximum source-receiver offset range compared with the target depth. Therefore, experiments in open waters use streamer lengths of 3-6 km. The actual locations of the hydrophone groups are determined by compasses in the sections in combination with a tail buoy. In heavy ice conditions (7-9/10 ice coverage) we used only a short streamer (max. offset range 500-800 m) without depth levelling birds and tailbuoy. Occasionally a mini-streamer of 100 m length (50 m active; for details see Tab. 2) was used. Birds and tailbouys would damage the streamer or would get lost interacting with drifting ice floes, since the streamer normally will be towed along or over ice floes during operation. A second problem was that the ship had to stop due to heavy ice conditions several times a day during the profile, and the seismic equipment had to be retrieved. Consequently, the use of a short cable minimized the required time for deploying and retrieving the towed streamer and airgun. For velocity determination we deployed sonobuoys as required.



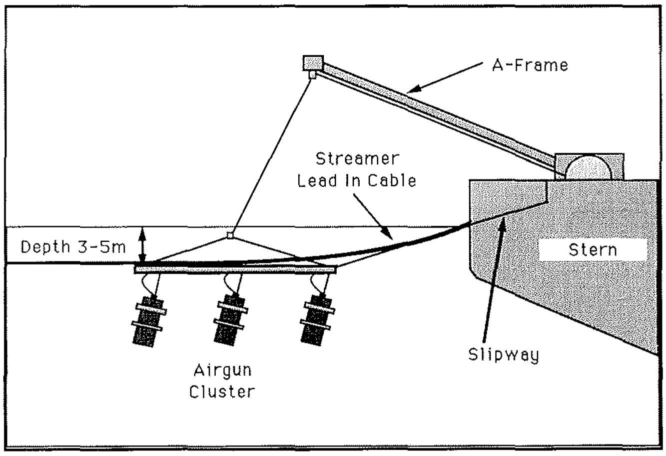


Fig. 3 : Basic sketch of towing technique for airgun cluster and streamer used. Please note that the airguns are towed close to the stern to minimize damage by drifting ice floes.

Abb. 3: Generelle Skizze der verwendeten Schlepptechnik für den Airgun-Cluster und den Streamer. Die Luftkanonen wurden sehr eng hinter dem Heck des Schiffes geschleppt, um Beschädigungen durch Eisschollen zu minimieren.

NOISE ANALYSIS AND DATA EXAMPLE

One of the most interesting question concerning acquisition before the cruise was if ship and ice floe generated noise would allow to identify any signals from the deeper layers (2-3 km) in the basins, especially to detect the top of the oceanic basement. We made special noise measurements during the cruise under different ice conditions (up to more than 2 m thick, Tab. 1). The recordings were carried out at the beginning and at the end of several profiles when no airguns were fired. At first, we wanted to investigate the noise caused by ship and ice separately. In a second step we made calculations for the signal/noise ratio which additionally depends on the sound source strength.

The dependence of the streamer noise level on the distance from the ship is shown in Figure 4. The highest RMS noise level was recorded during single ship seismic profiling (profiles 91090/91091) in 7-9/10 ice coverage. Peak values of 40 µbar were found on the near traces. A strong decrease in RMS noise down to 10 µbar can be observed after a second icebreaker supported the seismic measurements (profiles 91116/91126, Tab. 1) and occasionally the RMS noise level can be higher than 10 µbar (first channel, profile 91116). During open sea operations (profile 91133) the RMS noise level of the streamer equals -2.5 to 3.0 µbar for all channels, which are over 400 m away from the ship's stern (Fig. 4, from channel 9 on). The values of the signal to noise ratio for active lengths of 300 m and 50 m are displayed in Figure 5. The use of a streamer with an active length of 300 m and a heavier lead-in cable (6.1 kg/m in air) has increased the S/N value up to 20 db (a factor of 10) for the first channel close to the ship, and up to 40 db (a factor of 100) for the last channel of the streamer. In both cases we used the 24 l airgun array as a source. The use of the long streamer provided a S/N ratio greater than 1 until 800 ms for the first channel and until 1,800 ms for the last channel. Note the very low S/N ratio of the 50 m mini-streamer! An example of an unprocessed data set from the deep sea of the Amundsen Basin is shown in Figure 6a. Figure 6b shows the same data set but processed as a 2D line. The processing of the seismic data included the following mains steps:

CDP-Sorting (25 m)
Editing
NMO Correction
Frequency Filtering 10/20 to 90/110
CDP Stack (Median stack, 6-12 fold)
Automatic Gain Control

The major signal enhancements were produced by frequency filtering and median stacking of the data. In general, the seismic image did not improve significantly after detailed editing of the gathers. Some noise bursts could be suppressed only with minor success.

CONCLUSIONS

The data and towing techniques presented demonstrate that multichannel seismic measurements by ice breakers are possible in polar regions. It is important to mention that highly variable ice and weather (wind) conditions may cause expeditions to fail during a season. For safe seismic measurements under heavy ice conditions, we recommend the following :

- The streamer and the airguns have to be towed in the center of the ship's stern. The ship should have a slip to allow the streamer and the airgun supply cables to dive into the water close to the ship to avoid any uplifting of the equipment by ice floes.
- The occurence of strong noise bursts on the recordings and a higher noise level must be considered in general.
- No birds for depth levelling should be used. They can cause severe damage to the skin of the streamer if they collide with an ice floe.
- No tail buoy should be used. If any large floe drifts between the ship and the buoy, it is very likely that parts or the whole streamer will be lost.
- During severe ice conditions, a second ice breaker is essential for continuous seismic profiling. The leading ship can

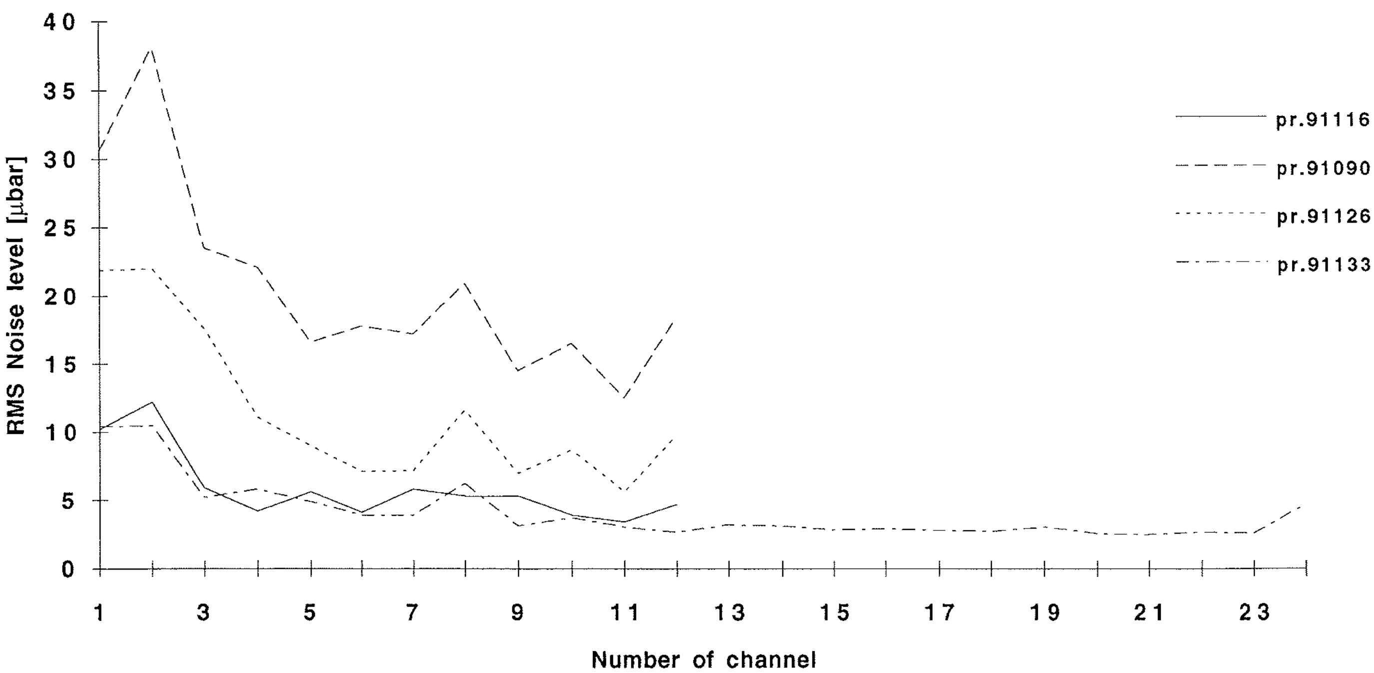


Fig. 4: RMS level of streamer noise versus offset of hydrophones (offset of first channel 180 m; spacing of channels 25 m).

Abb. 4: RMS-Level des Streamer-Noises aufgetragen gegen die Entfernung der Aufnehmerhydrophone (Entfernung des ersten Kanals ist 180 m; der Abstand zwischen den Kanälen beträgt 25 m).

Number of the Profile	RMS noise level (µbar) Number of streamer channels						Water depth (m)	Depth of streamer (m)					Active streamer length (m)	Ice conditions
	1	5	11	16	20	24		h1	h2	h3	h4	h5		
91020*	2957	2217											50	
91090*	30.2	16.6	12.4				3900						300	H(ice)=2-2.5m; D=100%
91091*	27.3	14.0	10.0				4300	8	18				300	H(ice)=2-2.5m; D=100%
91097	13.2	11.2	11.0				1200	21	14				300	H(ice)=2-2.5m; D=100%
91098	35.1	20.9	14.8				4220	6	9				300	H(ice)=2-2.5m; D=100%
91100	9.7	6.9	5.3				4350						300	H(ice)=2-2.5m; D=100%
91101	9.7	6.3	4.4				4370	10	10				300	Open channel behind the ship
91102	12.5	8.3	5.2				4360	6	6				300	H(ice)=2-2.5; x=200; D=100%
91102	8.3	9.2	5.4				4380	8	10				300	H(ice)=2-2.5m; D=100%
91106	14.8	8.5	5.9				4240	6	6				300	H(ice)=10-15cm
91107	10.0	5.8	3.7				4250	8	14				300	big lead during deploying
91108	7.1	4.9	3.4				3400	7	14				300	H(ice)=2-2.5m; D=100%
91110	11.1	9.4	8.8				1370	5	5				300	H(ice)=2-2.5m; D=100%
91112	12.9	9.7	9.7				1300	5	2				300	H(ice) 2.0m; floating ice in channel
91116	10.1	5.6	3.4				3885	8	6				300	H(ice) 2.0m
91126	21.4	9.1	5.6				990	3	4				300	H(ice)<2m; x=100m; D=100%
91127	26.0	10.9	5.0				835	2	7				300	heavy ice
91129	15.5	13.2	10.5				555	15	8				300	open sea
91130°	17.2	16.2	14.0	12.5	10.0	12.5	560	8	8	5	15	15	600	open sea; BN2; partly heavy ice
91133°	10.4	4.9	3.1	2.9	4.7	4.5	2040	4	10	5	11	8	600	open sea; BN4

Tab. 1: Summary of all noise recordings during the cruise ARCTIC'91. Operation of two vessels (one ice-breaker ahead) is marked. * Indicates profiles which were collected with a single ice-breaker only in heavy ice conditions. ° Indicates profiles which were collected in open waters. All other profiles were measured with the assistance of a second icebreaker.
x = length of open channel behind the ship; D = ice coverage in percent; BN = Beaufort Number; H(ice) = estimated thickness of sea ice; h1-h5 = position of depth sensors on the streamer;

Tab. 1: Zusammenfassung aller Noise-Aufzeichnungen während der Expedition ARCTIC'91. Der gleichzeitige Einsatz beider Schiffe (ein Eisbrecher voraus) ist markiert.

	Active Length (m)	Distance from source to first hydrophone	Hydrophone group interval (m)	Number of channels	Number of hydrophones per group	Sensitivity of hydrophones (8) (V/bar)	Weight of lead-in cable (kg/m)	Diameter of streamer (mm)
Short streamer	50	42	8.32	5	32	45.0	1.0	39
Long streamer	300	183	25.0	12	32	1.6	6.1	72

Tab. 2: Specifications fo the streamers used during the experiment. Note that the hydrophone sensitivity is related to one group consisting out of eight hydrophones. Four groups of each streamer were combined to one seismic channel.

Tab. 2: Technische Spezifikationen für die verwendeten Streamer. Die Angaben zur Hydrophone Sensivität beziehen sich jeweils auf eine Gruppe bestehend aus acht Hydrophonen. Vier Gruppen wurden jeweils zu einem seismischen Kanal gebündelt.

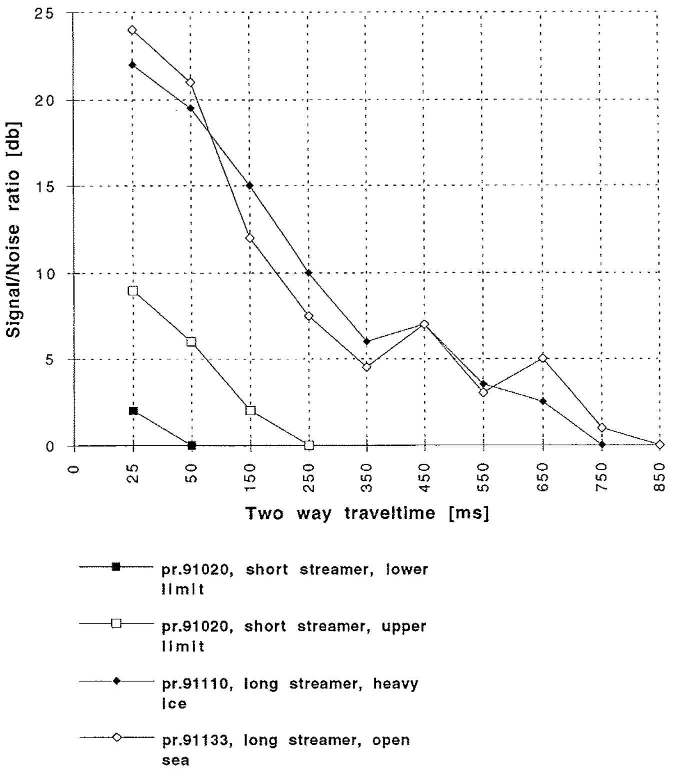


Fig. 5: Signal/Noise ratio of selected seismic traces.The ratio has been calculated within the time gates 0-50 ms, 50-100 ms, 100-200 ms etc. Zero is corresponding to the arrival of the first seismic signal (seafloor reflection).

Abb. 5: Signal/Rausch-Verhältnis ausgewählter, seismischer Spuren. Das Verhältnis wurde fur folgende Zeitfenster berechnet: 0-50 ms, 50-100 ms, 100-200 ms etc. Der Wert Null entspricht der Zeit des ersten seismischen Signals (Meeresbodenreflektion).

break through the ice in any mode, while the seismic ship is approaching slowly. The distance between the ships varies from 50 m to several hundred meters. The seismic vessel must also have good ice breaking capabilities, since the channel of the leading ship often closes very fast during heavy ice conditions.

In the design of a marine seismic towing system for ice covered regions, one has to consider that the airgun system is the most critical part of the equipment. As described above, several times the guns were almost lost. For generating a good seismic signal even when only a few guns are working, we strongly recommend the use of GI airguns, which provide an excellent signal even for a single gun operation. In general, the quality and results of the seismic data are far from those of measurements in open waters. For example, the streamer was too short compared to the mean water depth of 3000-4000 m and did not allow any accurate velocity determination from the curvature of the reflection hyperbolas. However, additional channels provided redundant data, which allowed the use of simple processing techniques in order to enhance the data quality without producing gaps in the recorded section. Despite the 7-9/10 ice coverage, the noise of the streamer, while using two ships, was surprisingly low (e.g. around 10 µbar, Tab. 1). Similar fair data quality could be collected in the Antarctic (Weddell Sea) considering the recommendations outlined above.

We think that a longer streamer can be used if the ice conditions allow. A good compromise, depending on ice conditions, may be a length of 1000-3000 m. Several experiments in the past off East Greenland (Hinz et al. 1991) and in the Weddell Sea, Antarctica, have shown that this is possible. For planning such kind of experiment the following aspects are important to note:

- A multi streamer experiment is not possible from our experience.
- A more or less regular seismic grid is only possible in easy ice conditions (up to 5/10 ice coverage). But even under these conditions the lines will not be straight.
- If one uses two icebreakers for the cruise, the source-receiver offset can be increased operating airguns from both ships.
- Ice/wind conditions can change within very short intervals, so that the ship might jam. The sea ice drifts with speeds of several kilometer a day and can close open water leads very fast. This means, the ship can be barred in the ice for days or weeks. Even an experiment with two ice breakers can fail under such conditions.
- Navigation in sea ice requires the search for open water or less severe ice conditions to optimize the ship's track. Here, ice reconnaissance by airplanes, helicopters or satellites is essential to guide the seismic vessel. Missing these facilities may lead to a situation where the ship steams into unfavourable ice conditions, while in some distance ice conditions are more favourable. Dense fog, however, can disable also the use of these means.
- In general, regional ice conditions vary from year to year. No valid long term predictions (6-12 months) of the ice conditions are available yet.

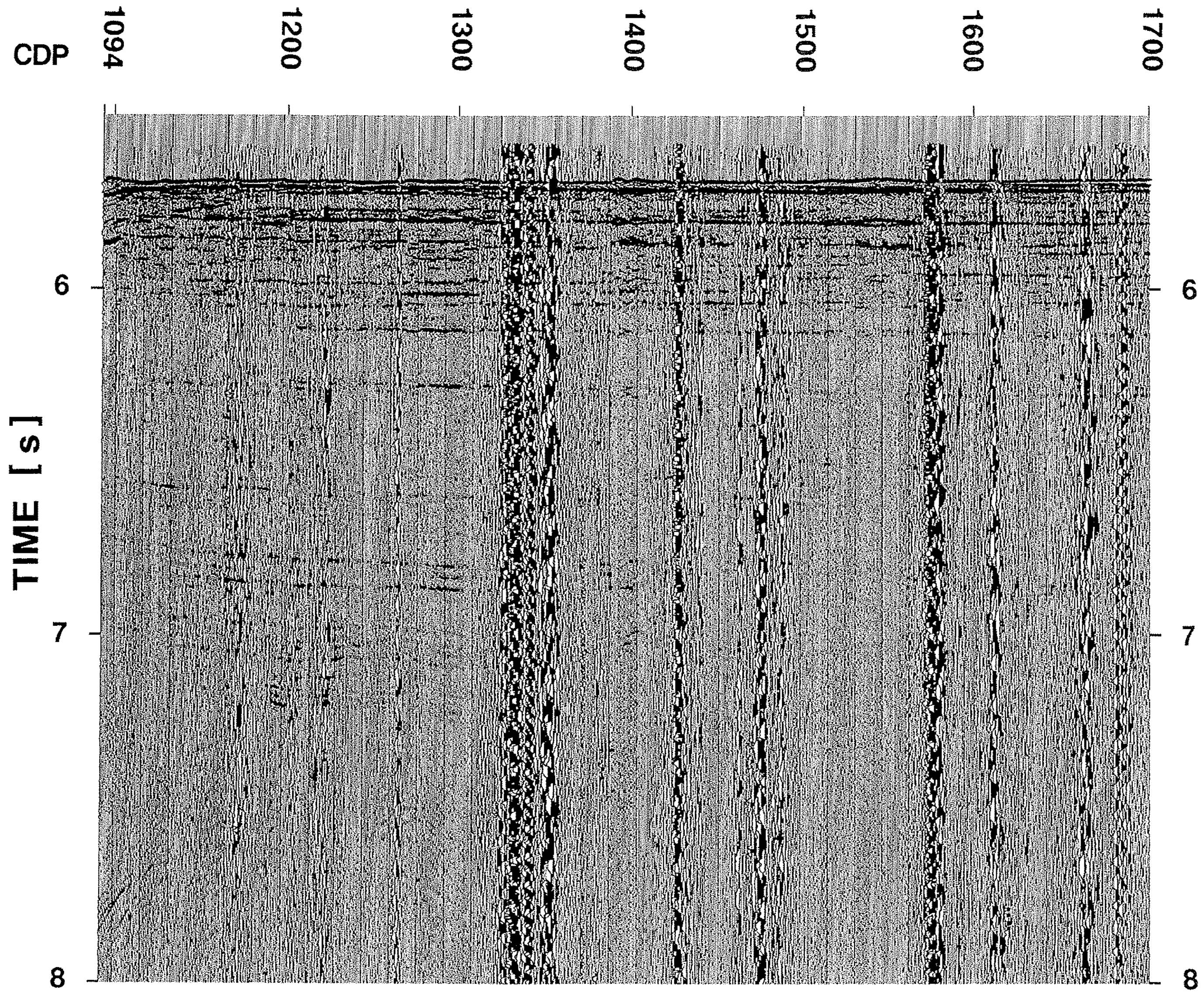


Fig. 6a: Common offset display of profile AWI-91098 (deep sea section; 4000 m water depth, 100 CDP ~2.5 km; channel 8) without processing steps applied. The profile is located approximately 70 km south of the North Pole. The strong events (noise bursts), e.g. between CDP's 1300/1400, are caused by collisions of parts of the streamer with ice floes. This was strongest when the ship had to make sharp curves (30-90° course changes) within short time intervals. Then, the streamer was dragged below the rough ice surface.

Abb. 6a: Common-Offset-Darstellung des Profils AWI-91098 (Tiefwasserbereich, 4000 m Wassertiefe, 100 CDP ~2.5 km; Kanal 8) ohne jegliche Bearbeitung. Das Profil befindet sich etwa 70 km südlich des Nordpols. Die starken Einsätze (Noise-Bursts), z.B. zwischen den CDP's 1300/1400, sind durch Kollisionen des Streamers mit Eisschollen verursacht worden. Diese Störsignale waren am stärksten, wenn das Schiff scharfe Kurven (Kurswechsel 30-90°) innerhalb kurzer Zeit

However, it should be noted that ships are not the only means for collecting marine-seismic data in the high latitudes. Recent discussions concerning the use of submarines and over-ice seismic profiling with a snow streamer (Kristoffersen et al. 1992) can and/or will provide additional acquisition techniques to collect seismic data from the sea ice covered polar regions in the future.

ACKNOWLEDGEMENTS

We are greatful for the support given by the captains and crews of the vessels *Oden* and *Polarstern*. Special thanks to Bernd Heesemann, who drew the technical figures. This is Alfred-Wegener-Institute contribution No. 850.

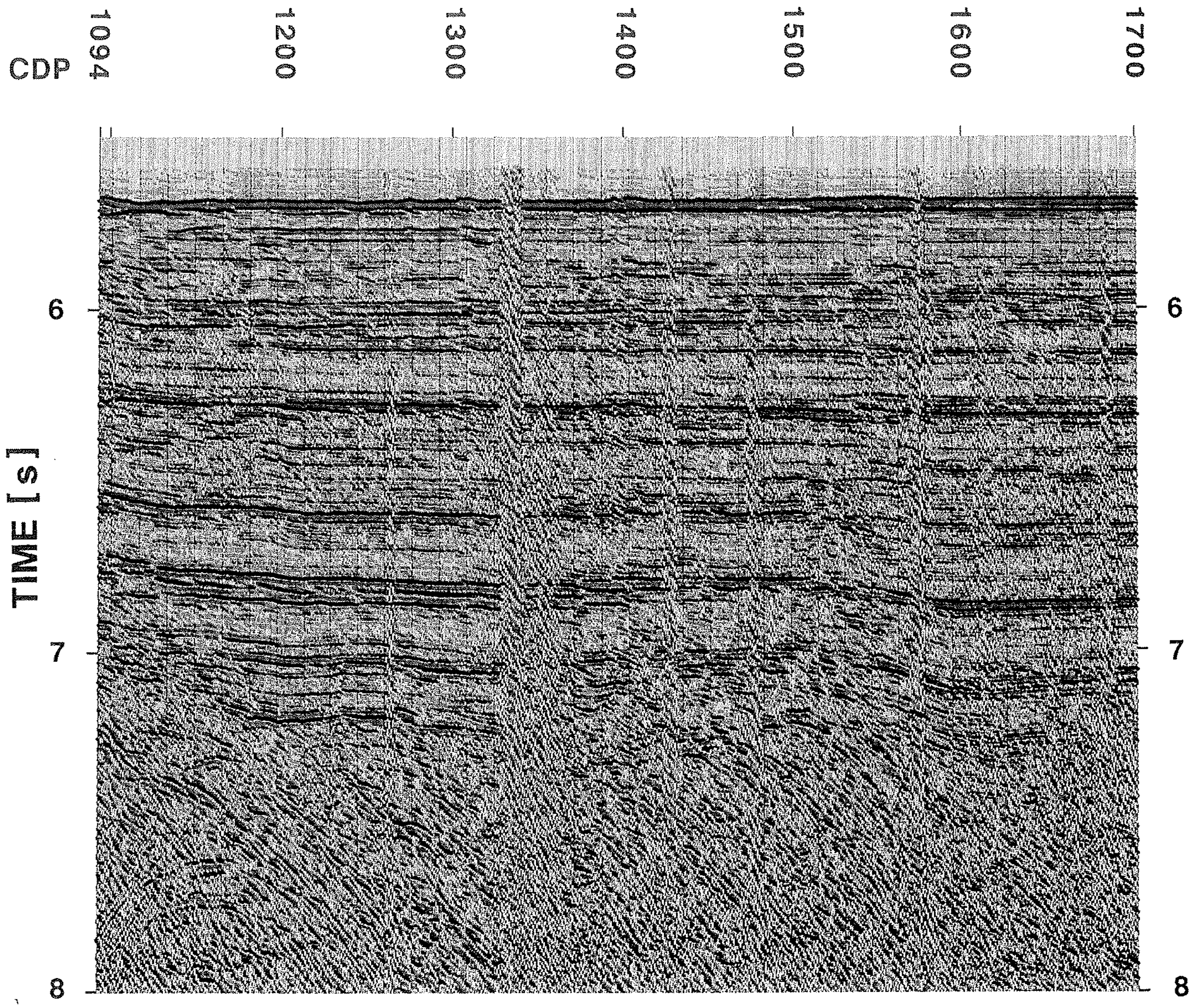


Fig. 6b: Profile AWI-91098 after signal enhancement and CDP stacking (100 CDP ~2.5 km). With rigorous editing, frequency filtering and median CDP stacking some of the noise bursts could be reduced. But some disturbances endured too long (several minutes) to make any seismic signals visible. Signals from the oceanic basement can be seen at approx. 7.3 s TWT.

Abb. 6b: Profil AWI-91098 nach der Signalverbesserung und einer CDP Stapelung (100 CDP ~2.5 km). Durch radikales Editieren, Frequenzfilterung und einer Median-Stapelung konnten einige der Störsignale deutlich reduziert werden. Andere Störeinflüsse dauerten hingegen zu lange (mehrere Minuten), so daß keine seismischen Signale mehr herausgearbeitet werden konnten. Einsätze der ozeanischen Kruste konnen jetzt deutlich bei etwa 7.3 s TWT erkannt werden.

References

Anderson, L.G. & Carlson-Lonnroth C.M. (eds.) (1991): International Arctic Ocean Expedition 1991, Icebreaker Oden - A cruise report.- Swedish Arctic Res. Programme 1991, 128 pp.

Behrendt, J.C. (1990): Multichannel seismic reflection surveys over the Antarctic continental margin relevant to petroleum resource studies.- In: ST. JOHN, B.S. (ed.), Antarctica as an Exploration Frontier - Hydrocarbon Potential, Geology, and Hazards, AAPG Studies in Geology 31, 69-75, Tulsa, Oklahoma.

Duckworth, G.L. & Baggeroer, A.B. (1985): Inversion of refraction data from the Fram and Nansen basins of the Arctic Ocean.- Tectonophysics 114: 55-102.

Forsyth, D.A., Asudeh, I., Green, A.G., Jackson, H.R. (1986): Crustal structure of the northern Alpha Ridge.- Nature 322: 349-352.

Fütterer, D.K. (ed.), (1992): ARCTIC'91: The expedition ARK VIII/3 of RV Polarstern in 1991.- Ber. Polarforsch. 107, 267pp.

Grantz, A. & May, S.D. (1992): The Alaska Aulacogen of the Arctic Mid-Ocean Ridge System.- EOS Trans. 73: 287.

Hall, J.K. (1970): Arctic Ocean geophysical studies; The Alpha Cordillera and Mendeleyev Ridge.- Ph.D. Thesis, Columbia University, 125 pp.

Hinz, K., Meyer, H,. & Miller, H. (1991): North-east Greenland shelf north of 79° N: results of a reflection seismic experiment in sea ice.- Marine and Petroleum Geology 8: 461-467.

Jackson, H.R., Reid, I., Falconer, R.K.H. (1982): Crustal structure near the Arctic Mid-Ocean Ridge.- J. Geophys. Res. 87: 1773-1783.

Jackson, H.R., Forsyth, D.A, Hall, J.K. & Overton, A. (1990): Seismic reflection and refraction.- In: A. GRANTZ, L. JOHNSON & J.F. SWEENEY (eds.),The Arctic Ocean Region, The Geology of North America Vol. L., 153-170, Geol. Soc. Amer., Boulder, Colorado,

Jokat, W., Alvers, M., Bouravtsev, V., Heesemann, B., Kristoffersen, Y., and Uenzelmann-Neben, G. (1992a): Marine Geophysics.- In: D.K.FUTTERER (ed.), ARCTIC'91: The expedition ARK VIII/3 of RV Polarstern in 1991, Ber. Polarforsch. 107: 108-129.

Jokat, W., Uenzelmann-Neben, G., Kristoffersen, Y. & Rasmussen, T.M. (1992b): Lomonosov Ridge - A double sided continental margin.- Geology 20: 887-890.

Jokat, W., Weigelt, E., Kristoffersen, Y., Rasmussen, T. & Schöne, T. (inpress): New insights into evolution of the Lomonosov Ridge and the Eurasian Basin.- Geophys. J. Internat.

Jokat, W., Weigelt, E., Kristoffersen, Y., Rasmussen, T. & Schöne, T. (in press): New Geophysical Results from the southwestern Eurasian Basin (Morris Jesup Rise, Yermak Plateau, Gakkel Ridge) and the Fram Strait.- Geophys. J. Internat.

Kristoffersen, Y. & Husebye, E.S. (1985): Multi-channel seismic reflection measurements in the Eurasia Basin, Arctic Ocean, from U.S. ice station FRAM IV.- Tectonophysics 114: 103-105.

Kristoffersen, Y., Fjellanger, J.P., Lif, A., Lingren, P.J.& Rasmussen, T. (1992): Over-ice seismic surveys. - In: D.K. FÜTTERER (ed.), ARCTIC'91: The expedition ARK VIII/3 of RV Polarstern in 1991, Ber. Polarforsch. 107: 121-124.

Mair, J.A. & Forsyth, D.A. (1982): Crustal structures of the Canada Basin near Alaska; The Lomonosov Ridge and adjoining basins near the North Pole.- Tectonophysics 89, 239-253.

Ulander, L., Carlstrom, A., Pallonen, J, Salmela, O. & Johannessen, B.J. (1991): Remote sensing and sea ice.- In: L.G. ANDERSON & M. CARLSSON-LONNROTH (eds.), International Arctic Ocean Expedition 1991; Icebreaker Oden - A cruise report, Swedish Arctic Res. Programme 1991, 60-73.