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. 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, Durekworth & Baggeroer 1985, Kristoffersen & Husebye 1985, Forsyth et al. 1986) 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, Andersson & Carlsson-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 tr 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 Eurasian 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).

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 continuous 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.


Marine Seismic Profiling in Ice Covered Regions

By Wilfried Jokat1, Vadim Yu. Buravtsev2 and Heinz Miller1

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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.

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
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 (31 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 tail buoy. Occasionally a mini-streamer of 100 m length (50 m active; for details see Tab. 2) was used. Birds and tail buoys 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.
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 91113) 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 1 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 main 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 occurrence 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 ice floes.
- 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 icebreaker is essential for continuous seismic profiling. The leading ship can

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.


NOISE ANALYSIS AND DATA EXAMPLE

One of the most interesting questions 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 91113) 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 1 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 main steps:

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- 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 icebreaker 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).

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

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

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

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 7/10 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. 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 corresponds to the arrival of the first seismic signal (seafloor reflection).

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

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.
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.

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 oceanischen Kruste können jetzt deutlich bei etwa 7.3 s TWT erkannt werden.
References


