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BROADBAND CALIBRATION OF MARINE SEISMIC SOURCES – A CASE STUDY

Introduction

1. At earlier meetings of the Committee for environmental protection there has been discussion of the problems associated with identifying the “footprint” of acoustic sources when in use in the Southern Ocean. Whilst there have been studies on research vessels elsewhere in the world no such data appeared to exist for research vessels operating within the CCAMLR or Treaty Area.
2. Earlier papers from SCAR have urged that Parties interested in developing a deeper understanding of the possible interactions between marine mammals and acoustic systems should undertake targeted research in order to provide the relevant data on which management proposals could be based.
3. The Alfred Wegener Institute undertook a characterisation of *Polarstern* with a characteristic air gun array, using a calibration system established in Norway.
4. This paper was presented as a draft at the Cadiz Workshop on marine acoustics and is submitted here as an example of the research that SCAR has suggested is needed. It will be submitted for publication to a scientific journal this year.

Conclusions

5. The model shows that the effective radii which might induce a Temporary Threshold Shift in marine mammals is 1-6 ship’s lengths and does not exceed 0.6 km.
6. The configuration used is at the lowest end of impacts in terms of air guns currently in use for marine geophysics.
7. The sound levels produced by natural events are of the same order as the source levels in the experiments although of a lower frequency content.
8. Spectral amplitudes drop off significantly in the higher frequencies, which is advantageous in terms of possible disruption of cetacean communications.

Broadband Calibration of Marine Seismic Sources Used For Academic Research in the Southern Ocean: A Case Study With R/V *Polarstern's* Airguns And Airgun Arrays

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1. Introduction

Academic seismic research in the Southern Ocean comprises both high-resolution reflection seismic surveys to study - for instance - the depositional history of fine-scale sedimentary structures, and lower-resolution, deep-penetrating reflection and refraction seismic surveys to study - for instance - large-scale crustal structures. These studies are usually embedded in research programs focussing on topics like the geodynamic evolution or the plate tectonic and paleoceanographic history of the Southern Ocean. Single airguns or airgun arrays of small size and volume and single- or multi-channel streamers are used as sound sources and receivers for high-resolution reflection seismic surveys, whereas airguns and airgun arrays of larger size and volume and ocean bottom hydrophones or seismometers and single- or multi-channel streamers are applied for lower-resolution, deep-penetrating reflection and refraction seismic surveys. To ensure that these research activities do not affect marine mammals in the Southern Ocean adversely and to better understand and mitigate potential impacts of sound sources a knowledge of their sound pressure field is essential. Therefore, as example, this paper describes a broadband marine seismic source calibration study conducted with R/V *Polarstern* at the Heggernes Acoustic Range, Norway in October 2003. The objectives were

(1) to determine the spatial distribution of the sound pressure levels emitted by the airguns and airgun arrays available at the Alfred-Wegener-Institute for Polar- and Marine Research, Bremerhaven, Germany in October 2003,

(2) to determine the frequency bandwidth, the spectral peak level and amplitude decay at higher frequencies, and the cumulative and total energy of the different source signatures,

(3) to determine the theoretical nominal source levels at 1 m distance by extrapolation of the measured far-field sound pressure levels assuming a spherical amplitude spreading,

(4) to determine radii within which according to the presently applied thresholds and the current scientific knowledge marine mammals might possibly experience behavioral or physiological disturbance or physical injury due to the received sound pressure levels.

Up to now thresholds defined by the National Marine Fisheries Service (NMFS), USA have often been used (NMFS, 2003). According to these regulations received levels greater than 180 dB_{rms} re 1 µPa might possibly cause hearing effects like temporary threshold shifts (TTS), and received levels greater than 160 dB_{rms} re 1 µPa might possibly lead to behavioral disturbances like avoidance of the sound source for cetaceans. For underwater pinnipeds received levels are allowed to be 10 dB_{rms} higher.

Recent studies on mid-frequency cetaceans like bottlenose dolphins (*Tursiops truncatus*) and white whales (*Delphinapterus leucas*) have shown that in addition to the (rms-) sound pressure level the signal duration and energy plays an important role whether and to which extent a TTS is induced. Tones (Finneran et al., 2005; Schlundt et al., 2000), octave-band noise (Nachtigall, 2003; 2004) and impulsive signals (Finneran et al., 2000; 2002b) have been used for these studies. By comparing the signal chararcteristics of a sperm whale click, a sonar ping and an airgun signal Madsen (2005) confirmed these findings and stated that an rms-level alone is unsuited as mitigative measure. In agreement with Finneran et al. (2002a, b) he recommended that both a maximum peak-to-peak received sound pressure level and a maximum received energy flux level should be used to mitigate the sound exposure of marine mammals, and the 90% energy approach should used for derivation of the signal duration

(Blackwell et al., 2004). During the 2nd meeting of the Marine Mammal Commssion in 2004, the Noise Exposure Criteria Group introduced first levels for the potential onset of TTS which take the different characteristics of impulsive signals (e.g. seismic airguns) and quasi-monofrequency tones of (e.g. sonars) in such a dual criterion into account (Noise Exposure Criteria Group, 2004). The criterion considers the peak pressure and the sound exposure level (SEL) or energy flux (cf. sect. 3.1) as function of signal duration and defines that a TTS is potentially induced if either a peak pressure of 224 dB re 1 µPa or a SEL of 183 dB re 1 $\mu Pa^2 s$ for impulsive signals or 195 dB re 1 $\mu Pa^2 s$ for quasi-monofrequency tones is exceeded. Based on studies on California sea lions (*Zalophus californianus*), harbor seals (*Phoca vitulina*) and northern elephant seals (*Mirounga angustirostris*) and due to precautionary principles thresholds are defined to be 20 dB lower for underwater pinnipeds (Finneran et al., 2003; Kastak et al., 1999; 2005). The 195 dB_{SEL} threshold for quasi-monofrequency tones is based on many TTS measurements consistently induced in bottlenose dolphins and white whales by tones and octave-band noise of different frequency and signal duration (Finneran et al., 2005; Nachtigall, 2004; 2003; Schlundt et al., 2000), and is therefore rather well established. The 224 $dB_{0\text{-}pk}$ and the 183 dB_{SEL} threshold for impulsive signals however presently relies on only one measured TTS induced in a white whale by a watergun signal (Finneran et al., 2002b) and is therefore possibly subject to change in future, when additional data and/or new scientific knowledge is available.

To give a complete overview in this paper we have determined the radii for both the 160, 170, 180 and 190 dB_{rms} levels of the rms-amplitude criterion and the currently defined 224 and 204 dB peak pressure and 195, 183, 175 and 163 dB_{SEL} levels of the peak pressure and SEL-based criterion.

2. Survey Layout and Data Recording

The source calibration study was conducted at the Heggernes Acoustic Range, near Bergen, in the Herdlefjord, Norway (Figure 1). The station is run by the Norwegian, Danish, Dutch and German navies for noise measurements of mainly NATO military, but civil vessels, too. It comprises a dynamic and a static test range. The dynamic test range used for this study consists of two chains á two hydrophones connected to the range station on the southern shore via cables. The water depth decreases from north to south and reaches ~380 m at the northern and ~200 m at the southern site. The northern hydrophones are positioned 263 and 198 m, the southern 100 and 35 m below the sea surface. The hydrophone chains are stabilized by a buoy 15 m above the upper hydrophone. The geographical positions of the chains are known. Their horizontal offset is 226 m.

The hydrophone systems are manufactured by Simrad, model type S-4009-I. They have an integrated preamplifier which allowed maximum sound pressure levels of ±5 $V_{pk\text{-}pk}$. The hydrophone systems were calibrated by the German Navy (WTD-71) before they were mounted into the chains. Their frequency response functions are almost flat between 3 and 5000 Hz with slightly different acoustic sensitivities of -168.6 (north upper), - 167.4 (north lower), -166.5 (south upper) and -166.1 ± 1 dB re 1 V/µPa (south lower) for each hydrophone system due to the different cable lengths to the range station. Taking the maximum allowable voltage of the preamplifiers into account only signals with peak-to-peak amplitudes less than 188.6 dB re 1 µPa were not clipped. The directivity pattern of the hydrophones is almost omnidirectional below 15 kHz, but introduces some distortions of maximum ±5 dB between 25 and 35 kHz in the spectra of signals with medium incidence angles (< 40°), and of maximum ±10 dB above 50 kHz for arbitrary incidence angles.

The data were sampled with a rate of 192 kHz after having passed an anti-alias filter with 80 kHz high-cut frequency and recorded continuously in the range station with a SONY SIR-1000W on trace 1 - 4. Depending on the received levels an analogue amplifier could be switched on in steps of 5 dB before digitization.

Table 1 gives an overview on the deployed airgun configurations. The 3-GI-gun array had a triangular, equilateral geometry with 2 m side length and 2 guns facing the ship's stern. It was shot once in "Airgun mode", i.e. Generator and Injector were fired simultaneously, and again in "True GI mode", i.e. the Injector was fired 33 ms after the Generator for an optimum bubble suppression. The guns of the 3-G-gun array were a sub-array of a 4-G-gun array with 2.5 m gun spacing, but with one of the inner guns not firing. The 8-VLF-gun array consisted of 2 lines á 4 guns mounted in a steel frame towed inline. Line spacing was 1 m athwart ship, gun spacing 1.2 m inline. Both lines are staggered by half a gun spacing, i.e. 0.6 m.

Both the single airguns and the tight airgun array geometries cause a directivity with an energy radiation slightly focussed downwards but no preferential azimuthal direction. Hence, shots from arbitrary directions are expected to be measured with the same level. So, the source calibration study confined to firing each airgun configuration along a line of 3 - 4 km length running between both hydrophone chains in NW-SE or SE-NW direction (Figure 1). The ship velocity was 5 kn. The ship position was determined by DGPS. A special GPS antenna provided by the German Navy (WTD-71) was mounted on *Polarstern's* top lantern amidship. In the range station, the received GPS data were recorded simultaneously with the seismic data on trace 7 of the SONY SIR-1000W.

The average sound velocity profile measured in the fjord close to the hydrophone chains is characterized by rather low values of 1448 m/s at the sea surface, maximum 1491 m/s in 16 m depth and 1481 - 1483 m/s in 76 - 240 m depth below the sea surface. This is due to rather low temperatures of about 8° at the sea surface, maximum 12° in 16 m depth and minimum 7 - 8° in 76 - 240 m depth, and - due to the numerous water falls - very low sea surface salinities of 6.5 ‰, which increase rapidly to 29.5 ‰ in 7 m depth and slowly to maximum 35.2‰ in 85 - 240 m depth below sea surface.

3. Data Analysis and Results

3.1. Single G-Gun

Post-processing includes a removal of the frequency response functions of the hydrophone systems and of the analogue amplifier gains so that the signal amplitudes give true sound pressure levels (in µPa). In what follows the data recorded and analyzed from the single G-Gun shots are discussed in detail as example for the source calibration study.

Figure 2 shows the seismogram sections recorded on both hydrophone chains. The arrivals of the direct wave were aligned to a constant time of 0.1 s to faciliate a later amplitude and spectral analysis of the primary signals. They are well separated in time from the sea floor reflections, and potential arrivals of a critical refraction at the sea floor are of negligible amplitude, so that the characteristics of the first arrivals can well be analyzed within a short time window, and the results are independent of the properties of the sea floor and subsurface. A comparison of the amplitudes of the direct wave indicates that they decay much faster on the shallower southern hydrophones than on the deeper northern hydrophones due to the Lloyd mirror effect; i.e. destructive interference of the direct wave and the ghost reflection causes almost vanishing amplitudes close to the sea surface and maximum amplitudes in several hundred metres depth leading to a "dipole-like" directivity even for single airguns (Parkes and Hatton, 1986). Unfortunately, amplitudes are clipped for short source-receiver distances, so that their primary waveforms and amplitudes were not further analyzed.

The subsequent data analysis was based on the "SEG Standard for Specifying Marine Seismic Energy Sources" (Johnston et al., 1988). According to this standard, the far-field signature, its amplitude spectrum or energy flux spectral density and its cumulative energy flux, "corrected" to 1 m distance by assuming spherical divergence, have to be presented as minimum requirement for a quantitative source description. This includes a quantification of the theoretical nominal peak-to-peak source level (in MPa), the pulse/bubble ratio and the SEL (in MPa^2s) or total energy flux (in J/m^2). Amplitude spectrum and energy flux spectral density as well as SEL and total energy flux are redundant and only differ by 182 dB due to a scaling by the acoustic impedance of sea water (Johnston et al., 1988).

A typical example are the seismogram, amplitude spectrum and cumulative energy flux of the single G-Gun shot fired 564 m (total slant range) away from the lower northern hydrophone (Figure 3). The pulse/bubble ratio could not be defined because of the interference of the weak bubble with reflections from the subsurface for relative times greater than 0.17 s. Theoretical nominal zero- and peak-to-peak source levels are 0.49 and 0.69 MPa or 234 and 237 dB re 1 µPa, respectively. The amplitude spectrum and the cumulative energy flux were computed from the gray-shaded 40 ms window including the primary pulse only. They show a spectral peak level of 182 dB re 1 µPa/Hz (0 dB re 1 $J/m^2/Hz$) at 77 Hz and a rather broad bandwidth of 16 - 166 Hz between the -3 dB points below the spectral peak level. The first notch occurs at 337 Hz. Spectral amplitudes decrease by about ~40 - 50 dB re 1 µPa/Hz within the 1 kHz range and continue to decrease for higher frequencies. 95% of the total energy flux of 0.32×10^{-3} J/m^2 (0.48×10^{-3} MPa^2s) is accumulated below 230 Hz.

Additionally, peak-to-peak, zero-to-peak, rms-amplitudes and SELs of the primary pulses were determined for each shot and hydrophone depth as function of source-receiver distance (Figure 4). According to the seismogram sections these graphs reflect the "dipole-like" directivity of marine seismic sources with low, rapidly decreasing amplitudes in the shallower southern and high, slowly decreasing amplitudes in the deeper northern hydrophone depths. As expected, peak-to-peak amplitudes are about 6 dB higher than zero-to-peak amplitudes and rms-amplitudes differ from SELs by 14 dB corresponding to the 40 ms window length (SEL [dB] = rms [dB] + 10 log τ, τ = window length in s; e.g. Madsen, 2005). A comparison between the amplitudes recorded during approach and departure from the hydrophone chains reveals a shadowing effect of *Polarstern's* hull. Amplitudes recorded at the same source-receiver distance are lower during approach than during departure indicating that the ship's hull deflects sound propagation forward the ship.

To follow the most conservative approach, i.e. the highest precautionary principles, source levels and radii, where according to current scientific knowledge a TTS is potentially induced or behavioral disturbances might occur (cf. section 1), were derived from the highest measured values recorded at the lower northern hydrophone. Theoretical nominal source levels were extrapolated from the peak-to-peak and zero-to-peak amplitudes recorded at the shortest source-receiver distance where amplitude were not clipped by assuming a spherical amplitude spreading. Radii were derived from the zero-to-peak, SEL and rms-amplitudes either by reading the corresponding source-receiver distances directly from the measured data or by determining it from a logarithmic least square fit to the measured data if the threshold lies outside the measured range of levels. The larger of the two distances derived from the approach and departure levels were taken. Radii were rounded off to the next higher multiple of 100 m, and below 100 m to 1, 10 or 50 m, respectively.

For the single G-Gun the shortest source-receiver distance where amplitudes were not clipped was 564 m with levels of 182 and 179 dB re 1 µPa for the peak-to-peak and zero-to-peak amplitudes and 152 dB re 1 μPa^2s for the SEL. From these values theoretical nominal peak-to-peak and zero-to-peak source levels of 237 and 234 dB re 1 µPa were computed (cf. Figure 3). The measured and extrapolated 160 and 180 dB_{rms} radii were rounded off to 900 and 300 m, respectively (cf. Figure 4c). The 224 $dB_{0\text{-}pk}$ and 195 or 183 dB_{SEL} thresholds were exceeded at ranges of less than 10 and 50 or 100 m (cf. Figure 4b, 4d). Hence, cetaceans might experience hearing disturbances like TTS within a radius of maximum 300 m in case of the 180 dB_{rms} criterion and of less than 50 or 100 m in case of the (pressure- and) SEL-based criterion. Potential behavioral disturbances by received levels higher than 160 dB_{rms} might be considered up to 900 m distance.

3.2. All Airgun Configurations

Similar far-field signatures, amplitude spectra and amplitude decay curves were derived for all airgun configurations and used to determine theoretical nominal source levels, spectral peak levels, frequency bandwidths, total energy fluxes, cumulative energies and radii for assumed TTS onset and behavioral disturbance (Tables 2 - 4). Generally, the single airguns and the airgun arrays cover a similiar range of values as their total volumes are on the same order. Theoretical nominal source levels vary between 229 - 243 $dB_{pk\text{-}pk}$ re 1 µPa and 224 - 240 $dB_{0\text{-}pk}$ re 1 µPa (Table 2). Spectral peak levels occur below 100 Hz, range from 182 - 194 dB re 1 µPa/Hz, and are about 40 - 50 dB re 1 µPa/Hz lower than the corresponding source levels (in dB re 1 µPa). Most of the signal energy of all sources is concentrated between about 5 - 150 Hz and amounts to 202 - 216 dB re 1 μPa^2s for the SEL (20 - 34 dB re 1 J/m^2 for the total energy flux). The radii for assumed TTS onset range from 200 - 600 m in case of the 180 dB_{rms} criterion (Table 3) and from 50 - 200 m or 50 - 300 m in case of the 195 or 183 dB_{SEL} criterion (Table 4). Zero-to-peak sound pressure levels fall below the 224 dB threshold already at ranges of less than 10 m and below the 204 dB threshold at ranges between 10 and 100 m (Table 4). Behavioral effects through received levels higher than 160 dB_{rms} might possibly be taken into account within ranges of 500 - 1900 m (Table 3). Generally, it is worth to mention, that due to the amplitude clipping only most of the 160 and 170 dB_{rms} radii could directly be derived from the measured data (standard letters in Table 3). The 180 and 190 dB_{rms} and all zero-to-peak pressure and SEL-based radii were extrapolated by the logarithmic least square fits to the measured data (italic letters in Tables 3 and 4).

4. Discussion and Summary

The source calibration study conducted at the Heggernes Acoustic Range with the airgun configurations available for R/V *Polarstern* in October 2003 has shown that the theoretical nominal source levels and the radii within which according to the current scientific knowledge the received sound pressure levels may potentially induce a TTS or disturb marine mammals' behaviour increase with source volume, as expected.

The radii within which a TTS might occur are generally on the order of 1 - 6 ship's length and do not exceed 0.6 km. Due to the rather small volumes of the seismic sources used in this study these radii are shorter than the 180 dB_{rms} radii determined for the larger-sized 10 - 20 gun arrays deployed by the R/V *M. Ewing* during a calibration study (Tolstoy et al., 2004).

The values of these radii, however, depend on the applied threshold criterion. If the 180 dB_{rms} threshold is applied the radii are about twice as large as in case of the 195 or 183 dB_{SEL} threshold. These values were derived for a window of 40 ms length including the primary signal only, without bubble and without subbottom reflections. Thus, these values characterize the pure far-field signature and can therefore be applied to each study, survey region and marine environment.

However, during marine seismic surveys marine mammals hear both the direct wave and the subbottom reflections. Hence, one could argue that longer time windows like the 90% energy approach for derivation of the signal duration (Blackwell et al., 2004) have to be used, which then do not characterize only the source signature but the survey region, too and have thus to be re-evaluated for each "new" marine environment. A re-analysis of the rms-amplitudes as function of window length (up to 1 s) for the single G-gun signal recorded on the lower northern hydrophone at 564 m range has shown that the radii derived from the 40 ms window rms-amplitudes (Table 3) are very conservative values which overestimate the 180 and 160 dB_{rms} radii by 11% if complete signals of 1 s length including subbottom reflections are taken into account. In contrast, a re-analysis of the SELs has shown that they are slightly higher if longer window lengths than 40 ms are used. Hence, the SELs of the far-field signature (Table 4) slightly underestimate the 195 or 183 dB_{SEL} radii by 3% if complete signals of 1 s length including direct and reflected waves are considered. Generally, the difference between the 195 or 183 dB_{SEL} radii evaluated for a 40 ms and a 1 s window is much smaller than the difference between the corresponding 180 dB_{rms} radii. This explains the large difference between the 180 dB_{rms} and 195 or 183 dB_{SEL} radii evaluated for a 40 ms window, whereas both radii are almost the same for a 1 s window.

The theoretical nominal source levels of the studied airgun configurations do not exceed those of the higher-frequency *Parasound (PS)* sediment and *Hydrosweep (HS)* multibeam echosounders installed in *Polarstern's* hull (SL_{PS} = 248 $dB_{0\text{-}pk}$ or 245 dB_{rms} @ 1 m for the primary frequencies 18 kHz and 20.5 - 23.5 kHz; SL_{HS} = 239.5 - 242 $dB_{0\text{-}pk}$ or 236.5 - 239 dB_{rms} @ 1 m for 15.5 kHz). Compared to other airgun arrays used for academic marine seismic research the maximum source level derived in this study for the Bolt PAR CT800 is 19 dB (~1/9th) lower than the theoretical nominal source level of the 20 gun array (140 l) used by the R/V *M. Ewing* (SL = 262 $dB_{pk\text{-}pk}$ re 1µPa; LGL Ltd., environmental research associates, 2003). Similarly, typical industry dual source arrays with 3 - 4 sub-arrays á 24 - 32 individual guns used for 3D seismic exploration have theoretical nominal vertical source levels of to 260 - 263 $dB_{pk\text{-}pk}$ re 1 µPa, depending on the frequency band (3 - 128 Hz or broadband up to ~25 kHz) considered (P. Fontana, pers. comm.), and are thus also 17 - 20 dB higher (~7 - 10 times) than the maximum source level of the Bolt PAR CT800.

The measured underwater sounds produced by baleen whales have significantly lower source levels, dominant frequencies of 18 - 30 Hz and signal durations of up to 25 s (Nieukirk et al., 2004). E.g. the peak source level of blue whale calls has been estimated to 188 dB re 1 µPa (Cummings and Thomson, 1971), and of fin whale calls to 183 dB re 1 µPa (Cummings and Thomson, 1994). In contrast, the echolocation clicks of toothed whales can reach significantly higher source levels. E.g. beaked whale clicks with source levels of 200 - 220 $dB_{pk\text{-}pk}$ re 1 µPa, dominant frequencies of up to 48 kHz and signal durations of ~200 µs (Johnson et al., 2004; Zimmer et al., 2005) and sperm whale clicks of up to 236 dB_{rms} re 1 µPa, dominant frequencies of 15 kHz and signals durations of ~100 µs have been measured (Møhl et al., 2003).

Natural events like submarine earthquakes or iceberg tremors cause ambient noise levels which are of comparable order than the source levels determined in this study, though the natural events are somewhat lower in frequency content. Hanson and Bowman (2006) derived a linear relationship (4 - 8 Hz) between the source level SL (in dB re 1µPa) of hydroacoustic events recorded in the Indian ocean and the seismic body wave magnitude mb, SL = 15.5 mb + 175, which shows that a seismic event of only magnitude 4.4 already causes a source level of 243 $dB_{pk\text{-}pk}$ re 1 µPa, the maximum source level determined in this study. Similarly, Chapp et al. (2005) recorded iceberg tremors with estimated source levels of ~245 $dB_{pk\text{-}pk}$ re 1 µPa.

The amplitude spectra of the airgun configurations studied here show that most of the energy of the marine seismic sources is emitted between about 5 and 150 Hz, with spectral peak levels below 100 Hz. Spectral amplitudes fall off by about ~40 - 50 dB re 1 µPa/Hz within the first kilohertz range and continue to drop for higher frequencies. This is important for marine mammals which are particularly sensitive to higher frequencies like toothed whales (e.g. Richardson et al., 1995) and particularly beaked whales (up to 48 kHz; Frantzis et al., 2002; Johnson et al., 2004; Zimmer et al., 2005), and which are often of great concern in discussions considering the effects of anthropogenic noise on marine mammals (Frantzis, 1998; Malakoff, 2002).

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Table 1. Characteristics of the marine seismic sources and survey parameters used during the source calibration study.

Airgun Types & Arrays	Volume[a] [l]	Pressure [bar]	Shot Interval [s]	Towing Depth [m]	Distance to Stern [m]
Single Airguns					
GI-Gun, Airgun Mode	0.7/1.7[b]	190	15	5	10
G-Gun	8.5	140	15	5	10
Bolt PAR CT800	32.8	130	60	10	30
Airgun Arrays					
3 GI-Guns, Airgun Mode	7.4	190	15	5	10
3 GI-Guns, True GI-Mode	7.4	190	15	5	10
8 VLF-Guns	24.0	120	15	5	10
3 G-Guns	25.6	140	30	5	15

[a]Original manufacturer-given volumes in cubic inch are converted to litre here, rounded to one decimal digit. In case of the airgun arrays, the total volume is first computed in cubic inch and then converted to litre.
[b]Generator/Injector volumes.

Table 2. Theoretical nominal peak-to-peak (SL_{pk-pk}) and zero-to peak source level (SL_{0-pk}), spectral peak level (Spec. PL) and corresponding frequency ($f_{spec.PL}$), bandwidth between the lower (f_l) and upper frequencies (f_u) of the -3 dB points below the spectral peak level, sound exposure level (SEL) and total energy flux of the far-field signature. All parameters were evaluated within a window of 40 ms length including the primary signal only, and "corrected" to 1 m distance by assuming spherical divergence (see text).

Airgun Types & Arrays	SL_{pk-pk} [dB][a]	SL_{0-pk} [dB][a]	Spec.PL [dB][b]	$f_{spec.PL}$ [Hz]	f_l - f_u [Hz]	SEL [dB][c]	E_{total} [dB][d]
Single Airguns							
GI-Gun, Airgun Mode	229	224	183	29	6 - 100	202	20
G-Gun	237	234	182	77	16 - 166	207	25
Bolt PAR CT800	242	239	194	28	5 - 143	216	34
Airgun Arrays							
3 GI-Guns, Airgun Mode	236	231	191	29	4 - 108	210	28
3 GI-Guns, True GI-Mode	241	238	187	77	21 - 143	211	29
8 VLF-Guns	243	240	191	32	9 - 154	214	32
3 G-Guns	241	237	191	35	13 - 112	213	31

[a]Peak-to-peak and zero-to-peak source level in dB re 1 μPa @ 1 m.
[b]Spectral peak level in dB re 1 μPa/Hz @ 1 m.
[c]Sound exposure level (SEL) in dB re 1 $\mu Pa^2 s$ @ 1 m.
[d]Total energy flux in dB re 1 J/m^2 @ 1 m.

Table 3. Radii where received sound pressure levels fall below the 160 - 190 dB_{rms} thresholds of the rms-amplitude based criterion, rounded off to the next higher multiple of 100 m. Rms-amplitudes were evaluated within a window of 40 ms length including the primary signal only (see text). Radii in standard letters were directly derived from the measured data. Radii in italic letters were derived from a logarithmic least square fit to the measured data, because they lie outside the measured range of values and are therefore not completely constrained by measured data.

Airgun Types & Arrays	190 dB[a]	180 dB[a]	170 dB[a]	160 dB[a]
Single Airguns				
GI-Gun, Airgun Mode	*100 m*	*200 m*	*300 m*	500 m
G-Gun	*200 m*	*300 m*	*500 m*	900 m
Bolt PAR CT800	*400 m*	*600 m*	1000 m	*1900 m*
Airgun Arrays				
3 GI-Guns, Airgun Mode	*200 m*	*300 m*	500 m	1000 m
3 GI-Guns, True GI-Mode	*300 m*	*400 m*	800 m	*1500 m*
8 VLF-Guns	*400 m*	*600 m*	1100 m	*1900 m*
3 G-Guns	*300 m*	*400 m*	800 m	1300 m

[a]Rms-amplitude thresholds in dB re 1 μPa @ 1 m.

Table 4. Radii where received sound pressure levels fall below the 224 and 204 $dB_{0\text{-}pk}$ and the 183 and 163 or 195 and 175 dB_{SEL} thresholds of the (peak-pressure and) SEL-based criterion, rounded off to the next higher multiple of 100 m or 1, 10 or 50 m respectively. SELs were evaluated within a window of 40 ms length including the primary signal only (see text). All zero-to-peak pressure-based radii (columns 1 - 2) were derived from the source levels given in Table 2 by assuming spherical divergence, and all SEL-based radii (columns 3 - 6) from the logarithmic least square fits to the measured data. All radii lie outside the measured range of values and are therefore not completely constrained by measured data, so that they are displayed in italic letters (cf. Table 3). A determination of the zero-to-peak pressure-based radii by extrapolation of the logarithmic least square fits (instead of extrapolation by spherical spreading) leads to slightly larger radii. However, in any case they are smaller than the SEL-based radii, so that in case of the dual criterion the SEL-based radii have to be considered for potential TTS onset.

Airgun Types & Arrays	224 dB[a]	204 dB[a]	195 dB[b]	183 dB[b]	175 dB[b]	163 dB[b]
Single Airguns						
GI-Gun, Airgun Mode	*1 m*	*10 m*	*50 m*	*50 m*	*100 m*	*200 m*
G-Gun	*10 m*	*50 m*	*50 m*	*100 m*	*200 m*	*300 m*
Bolt PAR CT800	*10 m*	*100 m*	*200 m*	*300 m*	*400 m*	*700 m*
Airgun Arrays						
3 GI-Guns, Airgun Mode	*10 m*	*50 m*	*50 m*	*100 m*	*200 m*	*300 m*
3 GI-Guns, True GI-Mode	*10 m*	*50 m*	*100 m*	*200 m*	*300 m*	*500 m*
8 VLF-Guns	*10 m*	*100 m*	*200 m*	*300 m*	*400 m*	*800 m*
3 G-Guns	*10 m*	*50 m*	*100 m*	*200 m*	*300 m*	*500 m*

[a]Zero-to-peak amplitude thresholds in dB re 1 μPa @ 1 m.
[b]Sound exposure level (SEL) thresholds in dB re 1 $\mu Pa^2 s$ @ 1 m.

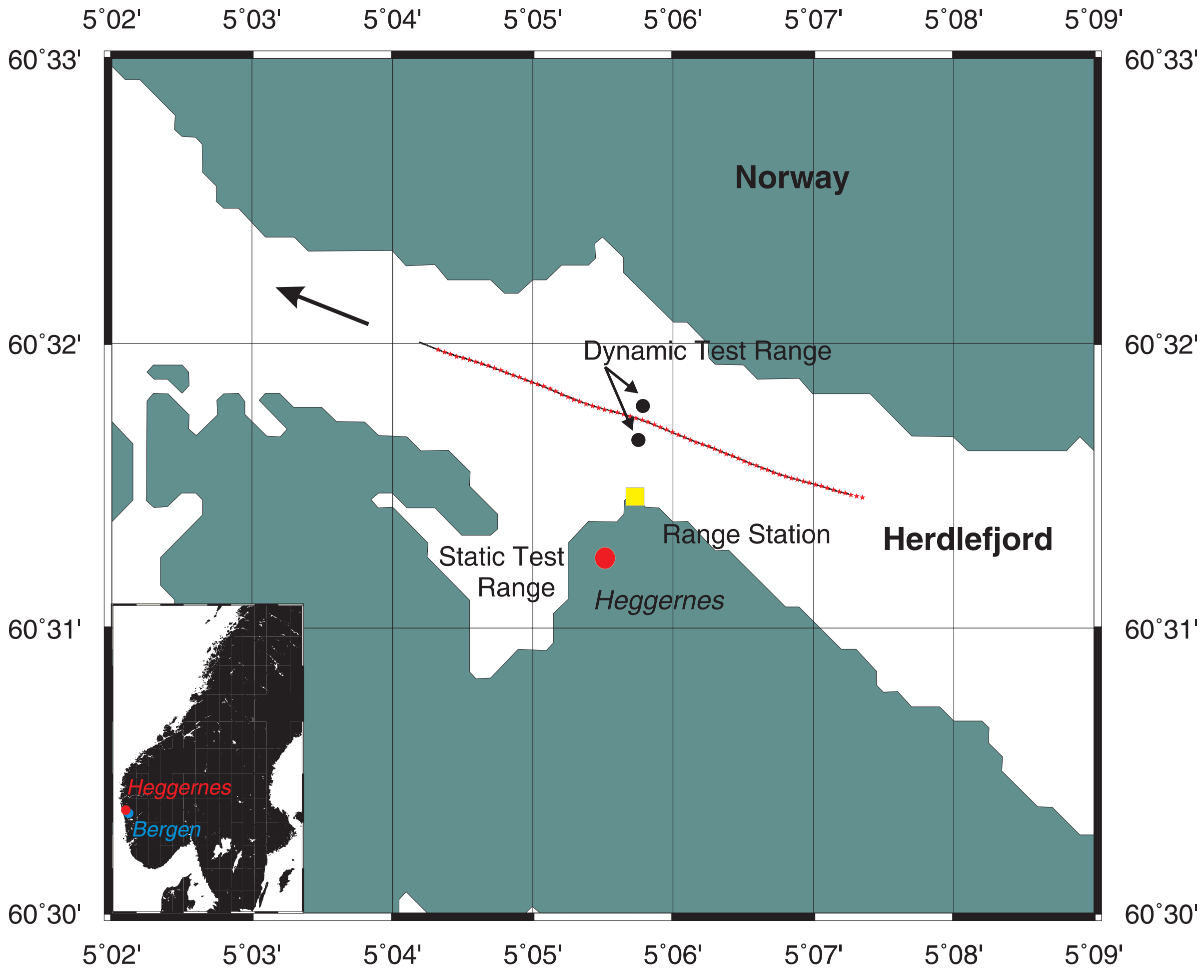

Figure 1. Map of the Heggernes Acoustic Range in the Herdlefjord, close to Bergen, Norway (see inset in the lower left corner). The black dots mark the positions of the two hydrophone chains. They are connected to the range station (yellow square), where the received data is digitally recorded. The arrow indicates the course and the black line the ship's track of one survey with one airgun configuration, here the single G-Gun as example. The red stars on the ship's track indicate the shot positions.

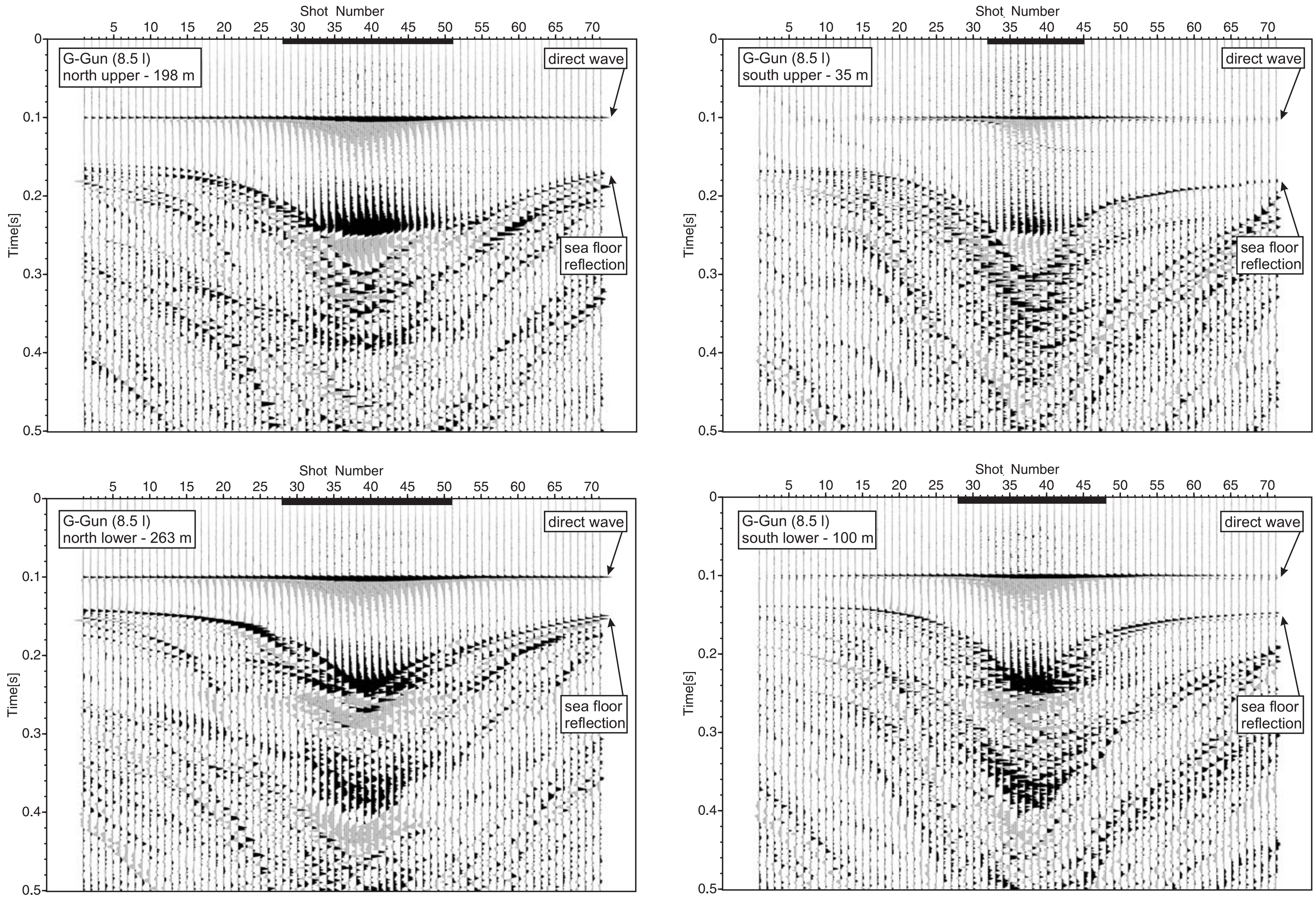

Figure 2. Common-receiver gathers of the single G-gun survey recorded at both hydrophone chains. The 4 different hydrophone depths and positions are indicated in the upper left corner of each seismogram section. The arrivals of the direct wave are aligned to an arbitrarily chosen constant time of 0.1 s to facilitate a later amplitude and spectral analysis of the primary signals. Instrument gains have been removed and amplitudes converted to Pascal, so that they can be compared from one seismogram section to the other. To enhance weak arrivals amplitudes are displayed 5fold exaggerated. The black bar on top of each section marks the shot numbers and traces with clipped amplitudes.

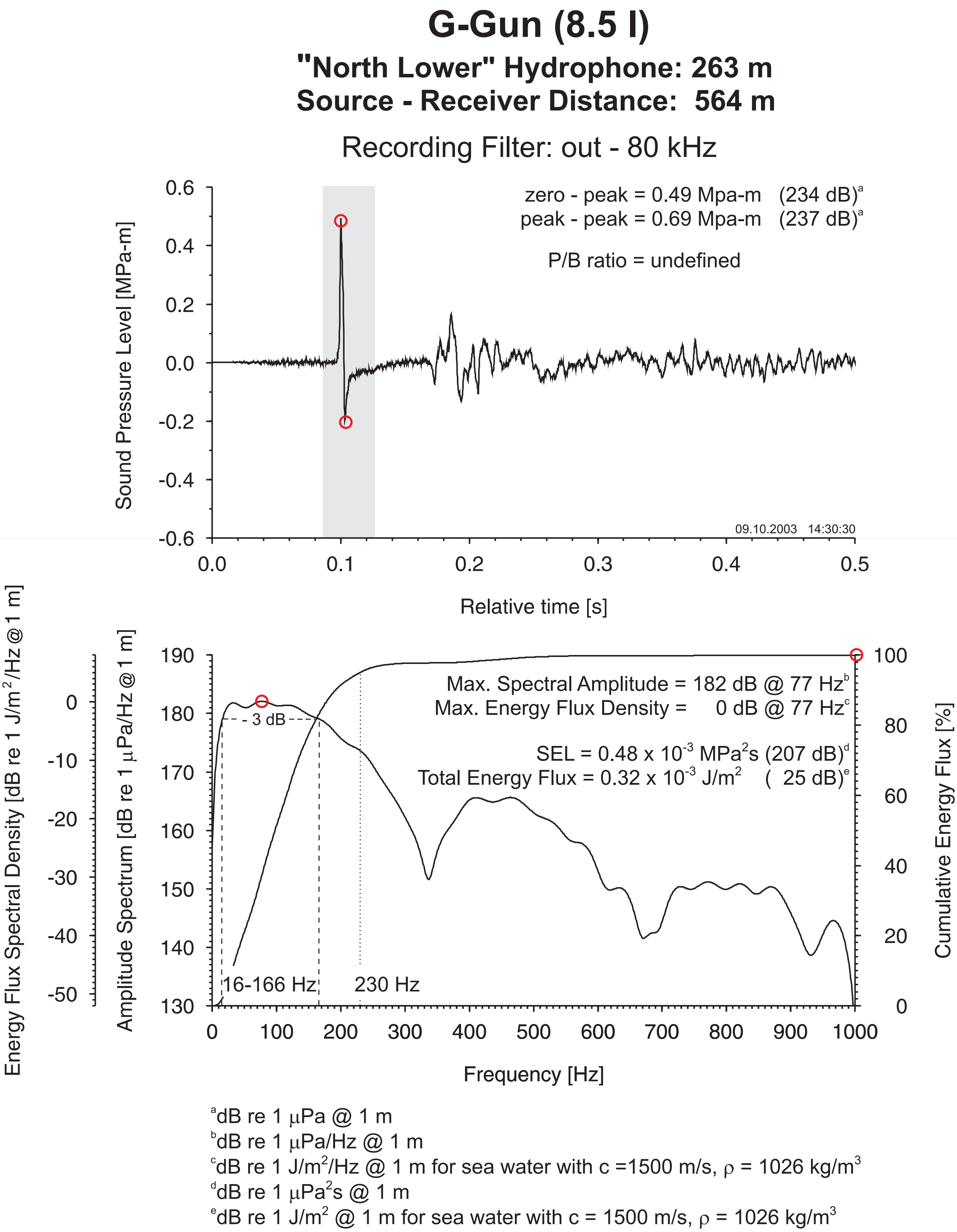

Figure 3. Far-field signature, amplitude spectrum and cumulative energy flux of the single G-Gun recorded at the lower northern hydrophone 263 m below the sea surface. The source-receiver distance of 564 m was the shortest distance where amplitudes were not clipped. Amplitudes were "corrected" to 1 m distance having assumed spherical divergence. The gray-shaded area indicates the 40 ms window (0.085 - 0.125 ms) used for the computation of the amplitude spectrum and cumulative energy flux shown in the lower part of the figure. The zero- and peak-to-peak amplitudes were derived from the far-field trace, the spectral peak level, the total energy flux and the sound exposure level (SEL) from the amplitude spectrum (red circles). The bandwidth (16 - 166 Hz) between the frequencies where spectral amplitudes are -3dB lower than the peak level is indicated by dashed vertical lines, the frequency (230 Hz) where 95% of the total energy flux is accumulated by a dotted line.

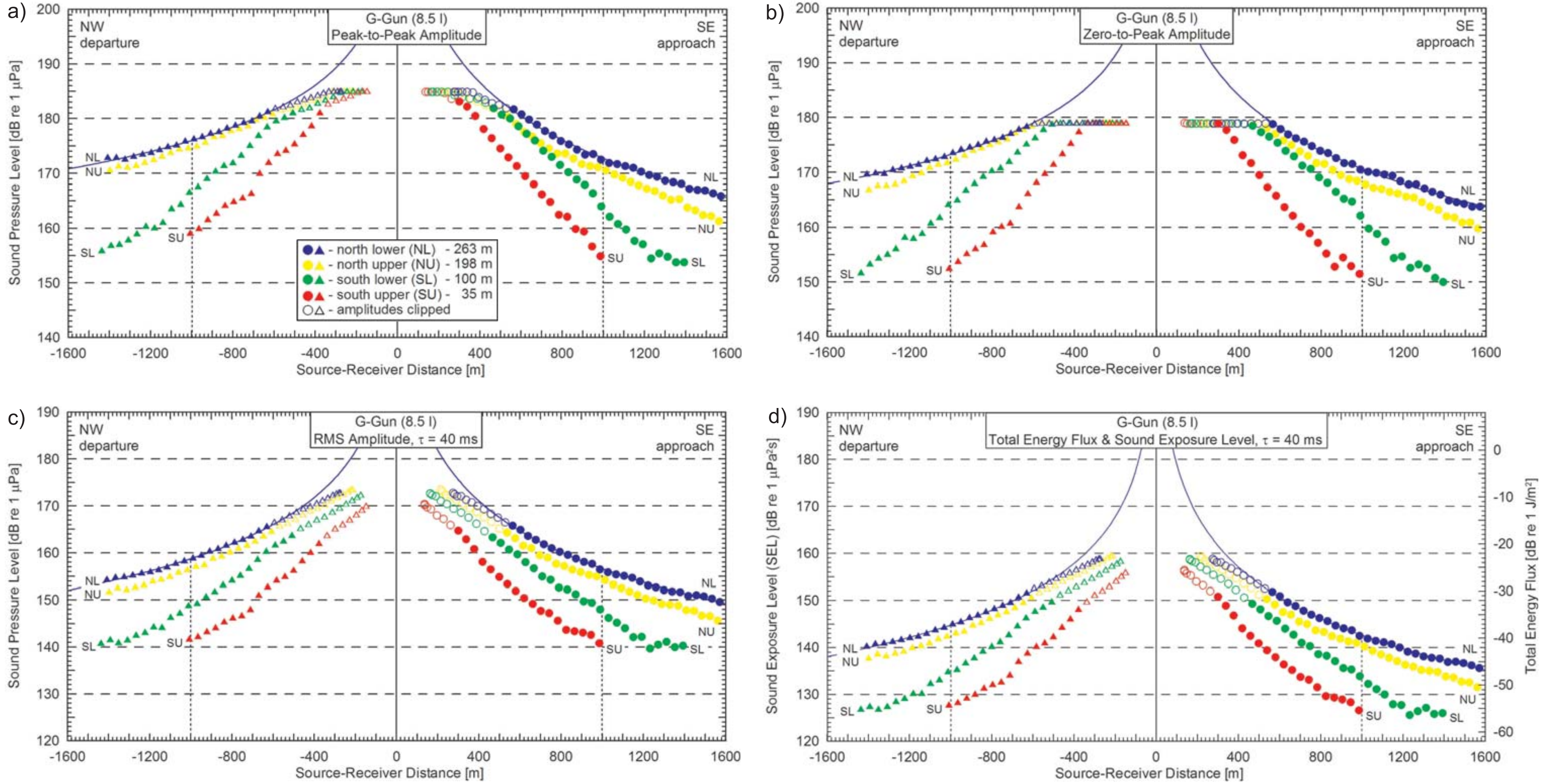

Figure 4. Peak-to-peak, zero-to-peak, rms-amplitudes and sound exposure levels (SEL) of the single G-gun survey as function of source-receiver distance, recorded at both hydrophone chains. A window length of $\tau = 40$ ms was used for the computation of the rms-amplitudes and SELs (cf. Figure 3). The 4 different hydrophone depths and positions are marked by colours (see legend). Open symbols indicate clipped amplitudes. Positive source-receiver distances are used for *Polarstern's* approach to the hydrophone chains, negative distances for its departure. A comparison of the amplitudes at ±1000 m source-receiver distance (dotted vertical lines) reveals a shadowing effect of the ship's hull resulting in lower amplitudes during approach than during departure. Logarithmic least square fits to the amplitudes recorded on the lower northern hydrophone (NL) are displayed as well. They are used to estimate radii for potential TTS onset or behavioral disturbance if the thresholds lie outside the measured range of values (see text).

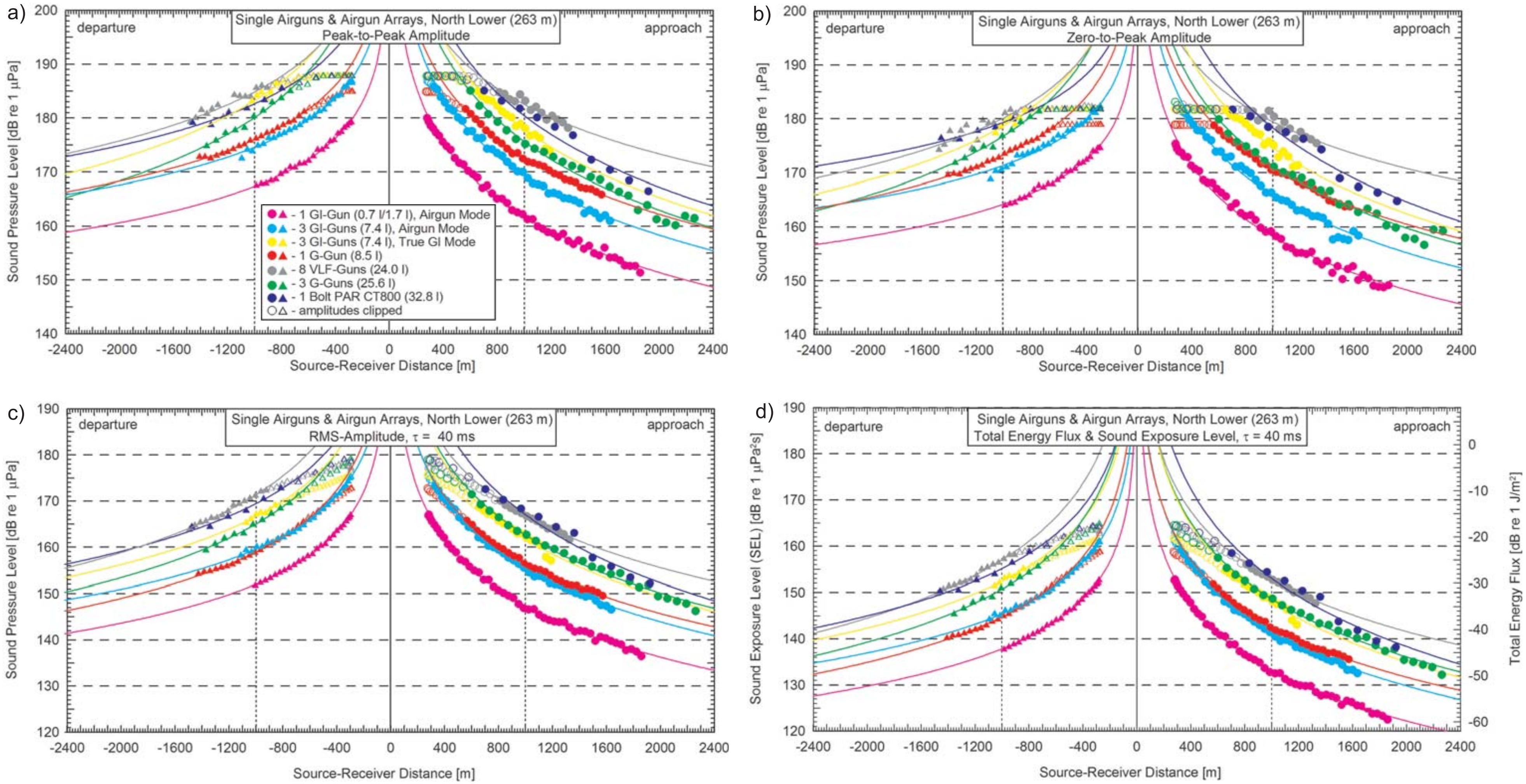

Figure 5. Peak-to-peak, zero-to-peak, rms-amplitudes and sound exposure levels (SEL) of all airgun configurations recorded on the lower northern hydrophone. A window length of $\tau = 40$ ms was used for the computation of rms-amplitudes and SELs (cf. Figure 3). The different airgun configurations are marked by colours (see legend). Open symbols indicate clipped amplitudes. Positive source-receiver distances are used for *Polarstern's* approach to the hydrophone chains, negative distances for its departure. A comparison of the amplitudes at ±1000 m source-receiver distance (dotted vertical lines) reveals a shadowing effect of the ship's hull resulting in lower amplitudes during approach than during departure. Logarithmic least square fits to the data are displayed as well. They are used to estimate radii for potential TTS onset or behavioral disturbance if the thresholds lie outside the measured range of values (see text).