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Assessment of potential for masking in marine mammals of the Antarctic exposed to underwater sound from airguns

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Assessment of potential for masking in marine mammals of the Antarctic exposed to underwater sound from airguns

by

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Abstract

Functional marine mammal acoustic communication evolved under natural ambient noise levels, which makes communication vulnerable to anthropogenic noise sources. In this report, we consider the potential long-range effects of airgun noise on marine mammal communication range. During the propagation process, airgun impulses are reflected multiple times from the sea surface, refracted in sound channels and reverberated, leading to signal stretching that may result in a continuous received sound. We modelled sound propagation using AcTUP (*Acoustic Toolbox User-interface & Postprocessor*) to estimate propagation loss and estimate the received seismic impulse waveform at 100, 500, 1000 and 2000 km distance from the source, and at 10, 50 and 200 m receiver depth for shallow (500 m) and deep sea (4000 m) Antarctic conditions. Modelled waveforms were overlaid with marine mammal vocalisations (song of fin whale *Balaenoptera physalus,* blue whale *Balaenoptera musculus intermedia* and Weddell seal *Leptonychotes Weddellii* vocalisations) to assess the distances over which communication masking could occur. Signals were analysed using a leaky integrator and peak detector model within the bandwidth of the modelled vocalisation. Hearing abilities of baleen whales were assumed to be noise limited at sea state 4. Results indicate that airgun noise is intermittent up to 1000 km from the source, changing to a continuous noise between 1000 and 2000 km. Results of masking modelling indicate that airgun sounds can lead to a significant loss in communication range for blue and fin whales at 2000 km from the source depending strongly on the frequency content of the vocalisation.

Kurzbeschreibung

Der akustische Informationsaustausch mariner Säugetiere hat sich in der natürlichen Geräuschkulisse der Weltozeane entwickelt und erlaubt die Kommunikation über große Entfernungen. Hinzukommende anthropogene Schalleinträge können die natürliche Kommunikation überlagern und stören. In diesem Bericht betrachten wir die potentielle Fernwirkung seismischer Luftpulser (Airguns) auf Kommunikationsreichweiten mariner Säugetiere. Airgun-Impulse werden während der Schallausbreitung mehrfach an der Wasseroberfläche reflektiert und in Schallkanälen gebrochen. Hierdurch entstehen Halleffekte, die die Signaldauer verlängern und schlussendlich zu einem kontinuierlichen Signal führen können. Um die Ausbreitungsverluste zu berechnen und das empfangene Signal zu bestimmen, wurde die Schallausbreitung mit AcTUP (*Acoustic Toolbox User-interface & Postprocessor*) für Entfernungen von 100, 500, 1000 und 2000 km von der Quelle modelliert. Die Schallausbreitung wurde für Empfänger in 10, 50 und 200 m Tiefe für flache (500 m Wassertiefe) und tiefe (4000 m Wassertiefe) Antarktische Gewässer berechnet. Die modellierten Störsignale wurden mit den Vokalisationen mariner Säugetiere überlagert (Gesang von Finnwalen (*Balaenoptera physalus)* und Blauwalen (*Balaenoptera musculus intermedia*) und Kommunikationslaute von Weddellrobben (*Leptonychotes weddellii*), um die Distanzen zu berechnen in denen Maskierung von Kommunikationssignalen potentiell vorkommt. Die Signale wurden mit einem mathematischen Hörmodell (*leaky integrator)* als Energiedetektor im Frequenzbereich der Vokalisationssignale analysiert. Es wurde dafür angenommen, dass Bartenwale Geräusche bis zu einem Pegel, der den regulären Hintergrundgeräuschen bei einem Seegang der Stärke 3-4 entspricht, wahrnehmen können. Die so analysierten Daten zeigen, dass Airgunimpulse bis zu 1.000 km von der Quelle als gepulste Signale empfangen werden und zwischen 1.000 und 2.000 km in ein kontinuierliches Geräusch mit tonalen Anteilen übergehen. Die Ergebnisse zeigen weiterhin, dass besonders für Finn- und Blauwale auch noch in 2.000 km Entfernung zur Schallquelle ein signifikanter Verlust an Kommunikationsreichweite auftritt. Diese Einschränkung ist in erheblichem Maße vom Frequenzspektrum der betrachteten Kommunikationssignale abhängig.

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List of Abbreviations

AcTUP	Acoustic Toolbox User-interface & Postprocessor
AIEP	German Act Implementing the Protocol on Environmental Protection of 4 October 1991 to the Antarctic Treaty (AIEP); In German: Gesetz zur Ausführung des Umweltschutzprotokolls vom 4. Oktober 1991 zum Antarktis-Vertrag (AUG - Umweltschutzprotokoll-Ausführungsgesetz);
APIS	Antarctic Pack-Ice Seals programme
AT	Antarctic Treaty
ATOC	Acoustic Thermometry of the Oceans Climate
ATS	Antarctic Treaty System
AUG	see AIEP
bp	band pass filter
BIWS	Bureau of International Whaling Statistics
BS	Breeding Stocks
CCAMLR	Convention for the Conservation of Antarctic Marine Living Resources
CCAS	Convention for the Conservation of Antarctic Seals
CITES	Convention on International Trade in Endangered Species
CMS	Convention on the Conservation of Migratory Species of Wild Animals
DASAR	Directional Autonomous Seafloor Acoustic Recorders
dB	decibel
EP	Environmental Protocol
f	frequency
FFT	Fast Fourier Transform
hp	high pass filter
Hz	Hertz
IDCR	International Decade for Cetacean Research
IUCN	International Union for Conservation of Nature
IWC	International Whaling Commission
JARPA	Japanese Whale Research Program Under Special Permit in the Antarctic
kn	knots (nautical miles per hour)
L_{eq}	Equivalent continuous sound pressure level
LI	leaky integrator
lp	low pass filter
ms	millisecond
µPa	micropascal (unit of pressure)

NM/nmi	nautical mile
Pa	Pascal – SI-unit of pressure
PTS	Permanent Threshold Shift
OAWRS	Ocean Acoustics Waveguide Remote Sensing
SCAR	Scientific Committee on Antarctic Research
SDR	Satellite-linked Dive Recorders
SEL	Sound Exposure Level
SL	Source Level
SNR	Signal to Noise Ratio
SO-GLOBEC	Southern Ocean Global Ocean Ecosystems Dynamics
SOWER	Southern Ocean Whale and Ecosystem Research
SOWS	Southern Ocean Whaling Sanctuary
SPL	Sound Pressure Level
TC	Time constant
TL	Transmission Loss
TTS	Temporary Threshold Shift
UBA	Umweltbundesamt (German Federal Environment Agency)
WS	Weddell Seal

1 Summary

Underwater noise is one of the sources of marine pollution whose ecological impact on marine mammals is not yet sufficiently investigated. Possible impacts of underwater sound on the marine environment have been discussed, and concern is expressed in several publications (Richardson et al. 1995; Gordon et al. 2003; Southall et al. 2007; Wright et al. 2007; Weilgart 2007; Di Iorio & Clark 2009; Melcón et al. 2012; Risch et al. 2012; Castellote et al. 2012). Marine mammals of the Antarctic are potentially adversely affected by the use of high power anthropogenic sound sources. Seismic airguns that are used for scientific seismic surveys in these areas produce high intensity, impulsive sounds with most energy in the very low frequency band which overlaps with many marine mammal vocalisations (e.g. songs and calls).

Marine mammals are highly dependent on their sense of hearing. The ability to acoustically perceive their environment is vital. Anthropogenic underwater noise may interfere with communication signals as well as predator, prey or ambient sounds that are of importance to the animal, and thereby mask an animal's ability to perceive these biologically important sounds (Gordon et al. 1998; Erbe 2000; Clark et al. 2009). Airguns have also been considered as having potentially deleterious effects (e.g. physical harm, behavioural reactions) at short distances of usually tens of kilometres (Yazvenko et al. 2007; Erbe & King 2009; Breitzke & Bohlen 2010; Gray & Van Waerebeek 2011). Masking, as a far-reaching effect however, was only partly considered within research studies and impact assessments and only few studies have considered the potentially adverse effect that masking by airguns can have on marine mammals (Streever et al. 2012).

Airgun sounds can be perceived above ambient sound levels over vast distances in water. During the sound propagation process, impulses are reflected multiple times on the water surface and refracted in sound channels (Urick 1983). Due to these processes the frequency content of the received signal at large distances as well as the length of the received wave form changes (signal stretching). The stretched signal may cover the whole period between successive airgun shots. Hence, the impulsive sound that airguns emit can develop continuous properties through sound propagation effects and may lead to a general increase in background noise level. Furthermore it may lead to continuous masking effects if received levels are above the hearing thresholds of marine mammals.

The Antarctic continent and the Southern Ocean south of 60°S are specially protected under the Antarctic Treaty (AT). The Protocol on Environmental Protection to the AT gives further protection to Antarctic marine mammals. In Germany the act is legally implemented by the AIEP[1] and permits for activities are issued by the German Federal Environment Agency (UBA). The scientific basis for assessing environmental effects induced by the use of airguns still shows considerable gaps. However, specifically masking of communication sounds, the inability to communicate in different noise conditions may have detrimental effects. Potential effects include amongst others the loss of opportunities to feed cooperatively, the loss of contact between mother and calf, but most importantly the loss of opportunites for finding mating partners. If these communications are masked to a high degree, it is feasible that population level effects occur.

This project aims at evaluating the potential masking effects of scientific airgun use in Antarctica.

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[1] Act implementing the Protocol of Environmental Protection of 4 October 1991 to the Antarctic Treaty (AIEP), BGBl. II 1994, 2478; entered into force on 14 January 1998.

Methodology

The evaluation whether there are potential masking effects was carried out in a three-step process. The first step was a literature review about the species concerned, their vocalisations, possible geographic and temporal overlap of the species with scientific airgun use and overlap in frequency content of propagated airgun signals and animal vocalisations. The Second step modelled sound propagation and the last step the masking potential.

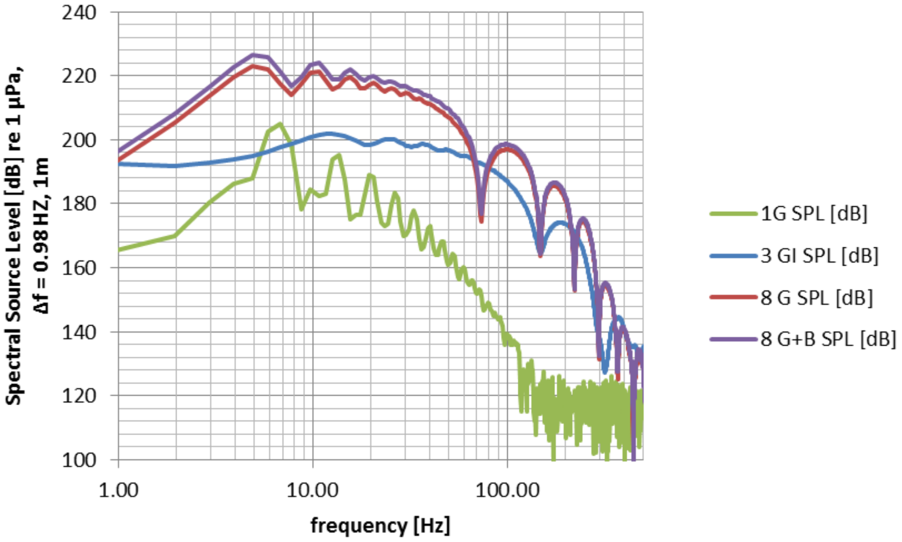
Literature Review

Within the study a thorough literature review on distribution, abundance and vocalisations of marine mammals occurring south of 60° S was conducted. The results are summarised in the report but can not be reproduced within a condensed form for this summary. Based on the results of the review three model species were selected: Blue whale (*Balaenoptera musculus intermedia*), fin whale (*Balaenoptera physalus*) and Weddell seal (*Leptonychotes weddellii*). For each of the species a characteristic vocalisations signal was searched and used for modelling: Z-calls of blue whales, 20 Hz pulse for fin whales and three types of Weddell seal vocalisations.

Sound Propagation Modelling

Sound propagation modelling was carried out for receiver positions at 100, 500, 1000 and 2000 km distance from the sound source using two flat model ocean depths of 500 and 4000 m on the basis of measured sound speed profiles. A third variable is receiver depth (10, 50 and 200 m are considered). Wave form of the airgun signal was taken from a previous study of an airgun array at 10 m source depth (notional signature) and was converted to a frequency spectrum via a Fast Fourier Transform (FFT) (Fig. 1-1). The signal is then propagated with AcTUP (Acoustic Toolbox User-interface & Postprocessor) to estimate Transmission Loss (TL) and the inverse FFT of the received signal is taken to reconstruct the wave form of the received airgun signal. Analysis was conducted using a mode summation algorithm which yielded similar results as a parabolic equation code but required less computing time. Water surface and sediment were assumed to be smooth and absorption was neglected. The results can therefore be considered as a maximum for the particular arrangement (source, receiver depth and sound speed profile).

Fig. 1-1 Frequency spectra for the time signals of all considered airgun configurations. For modelling of masking only the 8 G configuration (8 G—guns of 8.5 litres air chamber volume each) was used. 1 G – 1 G-gun of 8.5 litres, 3 GI – 3 GI-guns of 2.4 litres, 8 G+B – 8 G-guns of 8.5 litres and 1 Bolt PAR CT800 gun with 32.8 litre.



Masking Modelling

To limit the number of necessary calculations the analysis was limited to the model species and their characteristic vocalisations.

To take account of the impulsive nature of the airgun signals in different receiver distances (Fig. 1-1) and depth, it was decided that a model for the auditory processes would be necessary to characterize whether the communication signal of the animals can be detected during airgun use. The model for whale and seal hearing was chosen to be a leaky integrator combined with a level detector. This simple model was choosen as detailed knowledge on baleen whale hearing is not available at the moment. For hearing thresholds we assumed that baleen whales and seals are ‘noise limited’ and hence hear any signal in the low modelled frequencies above background noise corresponding to sea state 3-4 (according to ‘Wenz’-curves (Wenz, 1962) from hereon called ‘noise’; noise used in the modelling was actual background noise recorded at sea and scaled to 80 dB re µPa rms).

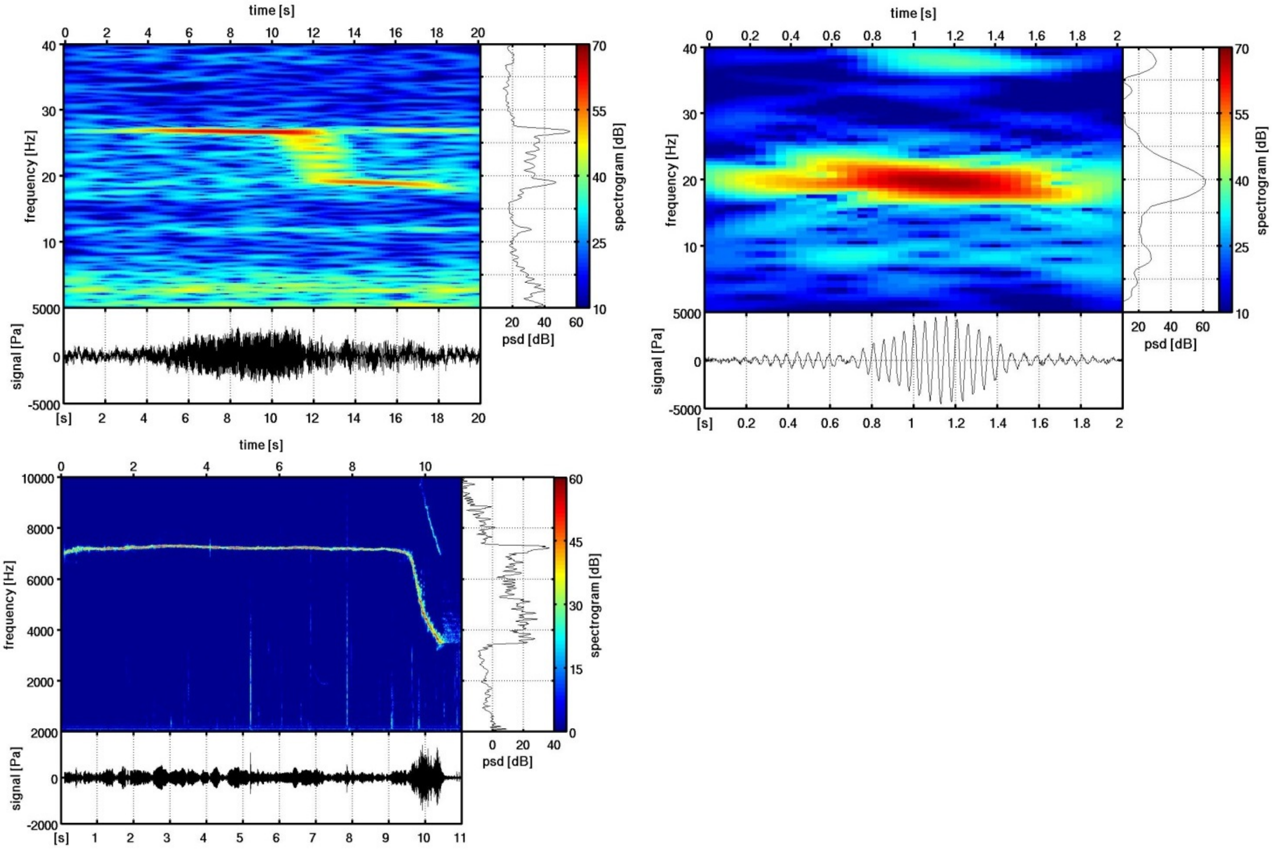
The modelling process covers the following steps:

Propagated airgun signal and noise are overlaid and the leaky integrator (LI) is run on noise alone to estimate the LI-output on noise alone (natural condition) and noise overlaid with the airgun signal (masked condition). All signals are band pass filtered in the same way as the animal vocalisations (see below).

- Animal vocalisations (Fig. 1-2) are
    - extracted from recordings, scaled to source level according to literature; duration and frequency bands are derived from the actual recording,
    - band pass filtered,
- a leaky integrator is designed using the total duration of the signal as a time constant (case of best possible detection) and
- in a second step the time constant of the leaky integrator was set to 0.2 s as a more reasonable estimate for the physiological time constant typical for mammals (Kastelein et al. 2010).
- Leaky integrator outputs are compared and masking distances are calculated. Examples for spectrograms of the signals used can be found in Fig. 1-2.
- It is unknown, whether the animals need to perceive the signal in full length for a detection. To test whether the results change drastically under the assumption that animals do not need the full length of the signal to detect their conspecifics vocalisations, we conducted a sensitivity analysis.

Source levels of the vocalisations were taken from the literature for blue whales (179 dB re µPa m, Samaran et al. (2010a)) and fin whales (189 dB re µPa m Širović et al. (2007)). The mean of reported source levels (Thomas and Kuechel 1982; Thomas et al., 1983b; Thomas and Stirling 1983) of approximately 173 dB re µPa m was used as an estimate for Weddel Seals.

Fig. 1-2 Input signals for masking modelling (top left: blue whale, top right: fin whale, bottom left: Weddell seal).



Signals were scaled to source and band pass filtered to account for the frequency range of the vocalisations. The propagated airgun impulses were filtered in the same fashion and leaky integrator outputs were compared to calculate masking distances. psd – power spectral density; the spectrogram shows the frequency content of the signal over time, colour values transfer into dB values as shown on the side bar.

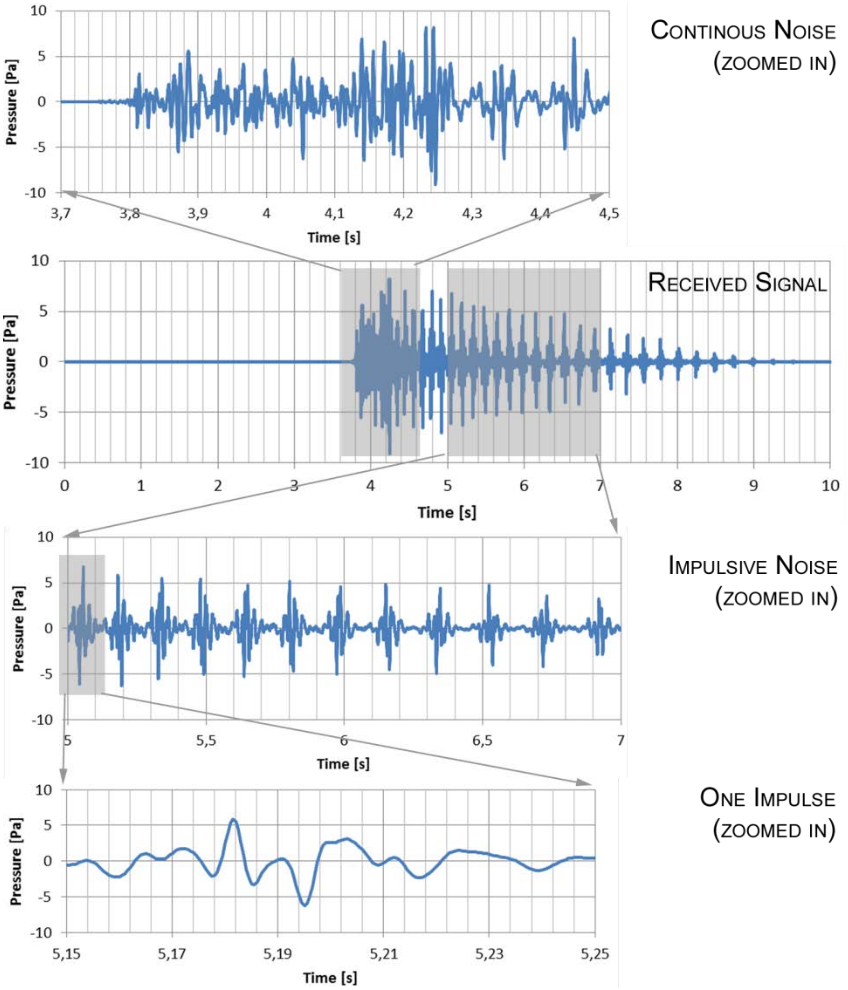
Results

Propagation Modelling

Results indicate that there is very little energy above 300 Hz. The models show that significant signal stretching can occur and will potentially lead to a continuous noise between 1000 and 2000 km distance from the airgun and beyond.

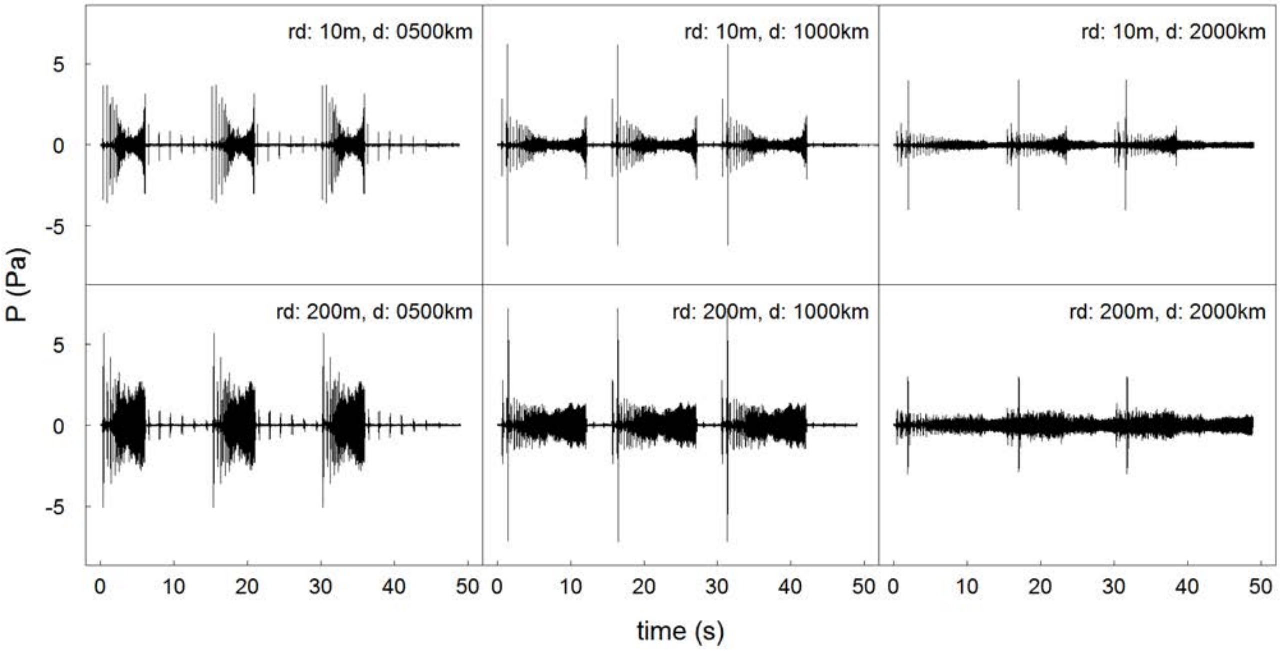
The result of sound propagation modelling for a received pulse in 100 km distance of the seismic source is depicted in Fig. 1-3. The wave form is stretched to almost 6 seconds while the received spectrum is still 60 dB above background noise. Hence, assuming a typical 15 s inter-shot-interval, the received signal at these distances is not continuous, but nevertheless covers a significant part of the available communication time which may hence already be masked. Due to mode dispersion, i.e. signals travelling different propagation paths and arriving therefore at different times at a receiver, the signal contains impulsive noise (multiple reflections) as well as continuous parts.

Fig. 1-3 Detailed view of a modelled received signal (at 100 km distance from seismic activity) showing continuous fluctuating and impulsive parts.



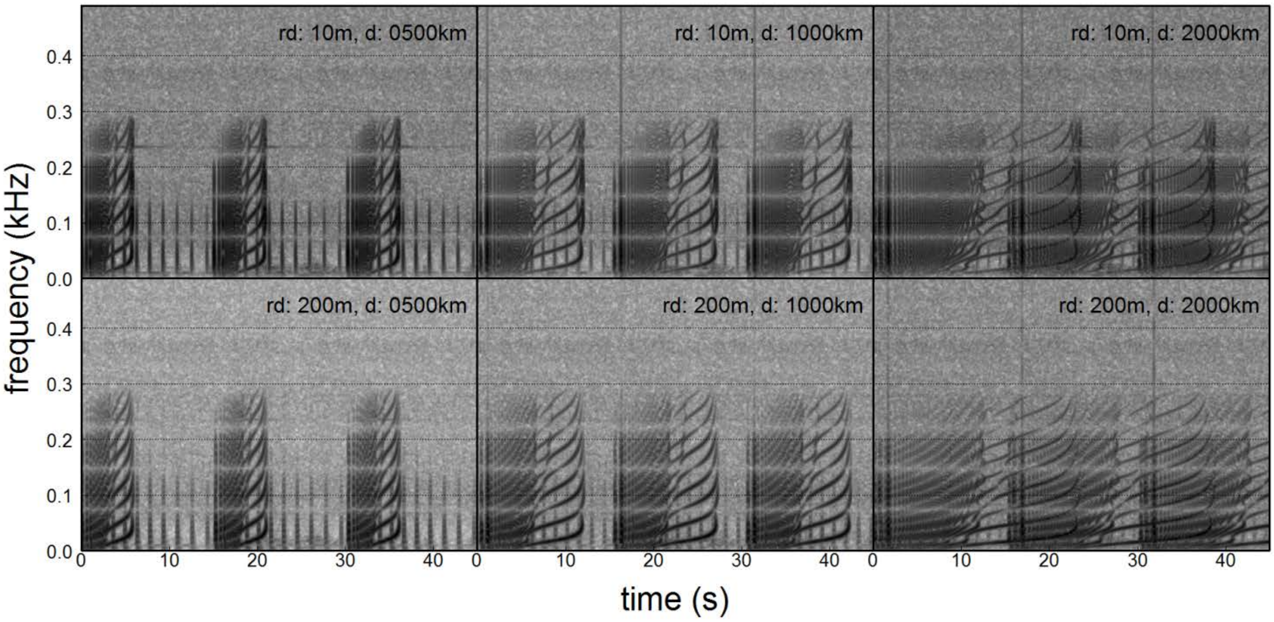
A more comprehensive overview of the results of propagation modelling can be found in Fig. 1-4 and Fig. 1-5 for deep conditions (4000 m receiver depth) showing a strong effect of signal stretching, that covers the whole time period between successive airgun shots in 2000 km distance. In shallow areas signal stretching does not have a linear relation to distance, nevertheless it is still considerable. The change of the signal from intermittent to continuous is presumably between 1000 and 2000 km. Within this project, we also tested whether masking effects may happen in intermittent noise.

Fig. 1-4 Input Signals (Airgun) for the masking modelling for deep areas (4000 m depth), rd: receiver depth, d: distance of modelled impulse from airgun, 8-G gun array with a volume of 8.5 litres each. Three impulses are shown to demonstrate how the beginning and ending of sequences would look like. Only the middle impulse was duplicated and used for further calculations.



Frequency spectra of the received waveforms (example in Fig. 1-5) show that the signals contain strong tonal sweeps either as up-sweeps for deep sea conditions, but to some extent also down-sweeps (not shown, compare Fig. 7-19) for shallow areas. Impulses may overlap with each other and hence the amplitude of the peaks may not drop consistently with distance, in contrast to the general noise level which does.

Fig. 1-5 Spectrograms of input signals (airgun) for the masking modelling for deep areas (4000 m depth), rd: receiver depth, d: distance of modelled impulse from airgun, 8-G gun array with a volume of 8.5 litres each.



Three impulses are shown to demonstrate how the beginning and ending of sequences would look like. Only the middle impulse was duplicated and used for further calculations. The spectrograms show that signals have tonal frequency content and hence a broadband measure is not sufficient for masking calculations.

Masking Modelling

18 different szenarios were modelled with regard to water depth, receiver depth and distance to airgun. The ratio between the natural communication range under natural background noise conditions (“no airgun”) and the communication distances for each case and species (“masked conditions”) give a relative measure for masking.

Results indicate that communication distances for all three species considered are reduced at 500 to 2000 km, but the effect strongly depends upon the frequency of the vocalisations considered. For three tested Weddell seal vocalisations for example the estimated masking potential was highly variable: masked communication distances ranged from 92 % (essentially no masking) to 1 % of the potentially undisturbed communication distance (see Table 1-1 for details on communication distances). For blue and fin whales the modelled loss of communication distance was between one and two orders of magnitudes (90 – 99 % loss of communication range).

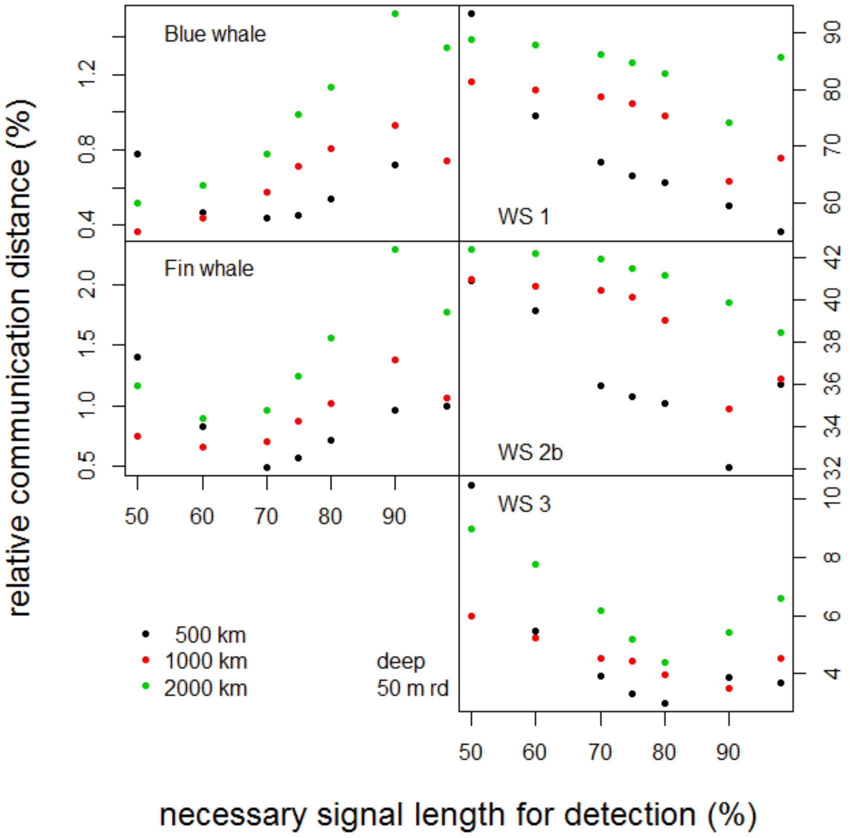
Table 1-1 Acoustic communication distances for the five vocalisations considered.

Case	Receiver Depth	Distance Airgun - Receiver	Water depth	Loss in acoustic communication distances (ratio of natural and masked communication distance [%])					
				Blue whale	**Fin whale**	**Weddell seal** Voc. #1	**Weddell seal** Voc #2a broad band filtered	**Weddell seal** Voc. #2b Narrow band filtered	**Weddell seal Voc. #3**
1	10	500	deep 4000 m	97.7%	96.2%	97.7%	98.5%	65.8%	99.1%
2	10	1000		97.8%	95.9%	97.8%	97.7%	82.9%	99.2%
3	10	2000		95.8%	91.5%	95.8%	96.5%	76.7%	98.6%
4	50	500		99.3%	98.9%	99.3%	98.4%	82.1%	99.4%
5	50	1000		99.3%	98.9%	99.3%	97.6%	77.7%	99.1%
6	50	2000		98.6%	97.7%	98.6%	96.2%	70.1%	98.7%
7	200	500		99.2%	99.0%	99.2%	96.4%	75.0%	98.5%
8	200	1000		99.0%	98.7%	99.0%	94.3%	77.7%	98.8%
9	200	2000		97.9%	97.3%	97.9%	91.8%	75.7%	98.0%
10	10	500	shallow 500 m	96.6%	95.0%	96.6%	98.5%	62.0%	99.1%
11	10	1000		93.2%	90.4%	93.2%	97.8%	60.3%	98.6%
12	10	2000		88.8%	82.0%	88.8%	96.4%	59.9%	97.7%
13	50	500		99.2%	98.9%	99.2%	98.5%	82.9%	99.5%
14	50	1000		98.5%	97.8%	98.5%	97.7%	75.2%	99.2%
15	50	2000		97.3%	96.0%	97.3%	96.1%	66.6%	98.7%
16	200	500		99.3%	99.3%	99.3%	96.6%	74.8%	98.6%
17	200	1000		98.5%	98.5%	98.5%	93.2%	65.0%	97.1%
18	200	2000		97.1%	96.8%	97.1%	87.0%	60.3%	94.2%

Spherical spreading was used as a model for sound propagation of the vocalisations, when using a time constant (TC) of 200 ms, seawater attenuation and assuming that 100 % free communication time is necessary for a detection. This table is an example for results of masking modelling. Different scenarios were considered and results are summarised in appendix C. Voc. – vocalization. The broad band filter of Weddell seal vocalization 2 included high frequency parts not overlapping with the frequency content of the airgun.

Communication ranges for blue and fin whales are drastically reduced, but the effect is not consistently in- or decreasing with distance. This indicates that masking is in fact happening in intermittent noise (for instance at 500 km, where a complete overlap of airgun signals is not given), as well as in continuous noise. The results for Weddell seals are highly variable and do not show a consistent pattern. Furthermore the Weddell seal vocalisation is a clear example that a better understanding of the hearing processes is crucial for an accurate implementation into the models: it consists of a high frequency part with higher energy content and a low frequency part with lower energy content. It was filtered with two different band pass filters and shows, that if the high frequency content is sufficient for a detection of vocalisation, then masking ranges are considerably reduced.

Fig. 1-6 Necessary signal length for a detection vs available relative communication distance (ratio between masked communication distance and natural communication distance; a relative measure for loss of communication distance). Even when the necessary signal length for detection is varied between 50 and 100, masking potential is changed only marginally.



For a receiver depth of **50 m**, deep sound propagation model and the tested signals, deep sound propagation model (4000 m water depth), WS-Weddell Seal. While masking expressed as relative available communication compared to natural communication distance decreases with distance towards the airgun array, magnitudes of potential masking are comparable although different necessary signal length for detection is assumed: Fin whales and blue whales have approximately 0.4 to 2 % of their natural communication distance, while the output drastically varies for Weddell seals depending on vocalisation type tested. The relationship is hence highly dependent on the animals' vocalisations and cannot be expressed as a simple model. Graphs for all cases can be found in Appendix C.

Fundamentally we assumed within this study that animals need to receive the full signal unmasked to be able to detect it. Signals of baleen whales are long and hence it could be the case, that they do not need the full signal length for detection. To test whether this assumption has a large influence on the outcome we conducted a sensitivity analysis. Fig. 1-6 shows the relative communication distance (communication distance in masked conditions relative to calculated natural conditions) when we assume that animals do not need the full signal duration for the detection of a conspecifics vocalisation. The interesting outcome is, that while masking ranges do change, when the necessary signal length for detection is varied, it does not change the magnitude of the ratio of masked and natural communication ranges even though animals would be assumed to need much less time to detect the signal of a conspecific if we assume that necessary signal length is e.g. 50 % instead of 100 %. The receiver depth as another input variable does not change those results drastically either.

Discussion

According to our results it is very likely, that:

- the modelling results for sound propagation are valid: The modelled received impulses are comparable to real received signals of airgun impulses.
- airguns can considerable mask communication of marine mammals at distances of 500 - 2000 km. This applies for animals preferably using the upper water column (0-200 m) and vocalizing in the low frequency range (< 100 Hz).
- for fin and blue whales communication ranges decrease significantly.
- communication of animals using frequency bands above 300 Hz is most likely not affected to the same extent.
- seals are most likely less affected, but especially the low frequency, long carrying parts of their vocalisations may be masked.
- masking potential is higher for sound propagation in deeper areas.
- fluctuations in the airgun signal result in an intermittent noise in medium distances between 500 and 1000 km.
- communication of blue and fin whales is masked considerably even in intermittent noise in distances modelled between 500 and 1.000 km as variation of the necessary signal length for detection only insignificantly changes the modelled masking results. As the background noise shows similar fluctuations, the natural as well as masked communication ranges does increase, the ratio however does not change much

The results presented here are a first approach to predict loss of acoustic communication range by seismic airguns. Given that all underlying assumptions are valid, the modelled reduction in available communication space would have most probably a serious effect on individual and population level. However, knowledge on baleen whale hearing and data availability for validating sound propagation models is limited. Data are available from large receiver depths (where most mammals do not occur), and recordings made mainly close to the water surface (alike occurrence of baleen whales to about 200m depth) is currently limited in bandwidth. However, a serious model evaluation using real data must be conducted before the quantitative results of this study are used in a conservation context. In the meantime the precautionary principle should be applied. Especially the modelled received levels of the airgun signal have a very strong influence on the masking model outcome and have to be considered as worst case estimates in this study. Hence, masking ranges are most likely overestimates. Critical information on baleen whale hearing, like for instance critical signal-to-noise ratios and the ability to detect sounds from different angles of incidence in better accuracy, will most probably alter the results as well.

The approach to use a leaky integrator as a model for detection of the received signals has provided much insight due to the possibilities to use different amount of overlap between airgun and vocalisation and the possibility to vary parameters like the time constant of integration. However, restrictions are that the leaky integrator cannot cope (at the moment) with the ability of animals to detect signals from different incidence angles with higher precision (directivity index). This is based on the animals' ability to estimate a bearing towards a sound source. With increasing angle between two sound sources it is much easier to separate them. There are no data available to predict directional hearing in baleen whales. This caveat may be addressed in the context of controlled exposure experiments.

One important point that could not be addressed within this project is passive listening. Animals get much information from listening to their surrounding soundscape for prey, predators and natural sound events. If these sounds are indeed masked, then significant consequences may occur. However, we have no valid assumptions to model these effects at the moment and hence have to restrict our analysis to cases, where valid assumptions can be applied.

It is evident that further research is needed, however, until more information and data are available potential population level effects of masking from seismic sources must be considered in conservation efforts with regard to the precautionary principle. The results of this study show, that masking in very large distances is a possibility and can not be neglected. The developed model can now be adapted according to new research results and can be fitted to other model species.

2 Zusammenfassung

Unterwasserlärm ist ein Energieeintrag in marine Ökosysteme, dessen ökologische Auswirkungen auf marine Säugetiere noch nicht ausreichend untersucht worden sind. Viele wissenschaftliche Veröffentlichungen diskutieren die möglichen Einflüsse von Unterwasserschall auf die Meeresumwelt und äußern Bedenken über ihre Auswirkungen. (Richardson et al. 1995; Gordon et al. 2003; Southall et al. 2007; Wright et al. 2007; Weilgart 2007; Di Iorio & Clark 2009; Melcón et al. 2012; Risch et al. 2012; Castellote et al. 2012). Die marinen Säugetiere der Antarktis werden potentiell durch die Nutzung von energiereichen anthropogenen Lärmquellen beeinträchtigt. Seismische Luftpulser (so genannte Airguns), die für wissenschaftliche seismische Untersuchungen verwendet werden, erzeugen ein lautes, impulshaftes Schallsignal, das die meiste Energie im tieffrequenten Bereich besitzt. Dieser Frequenzbereich überschneidet sich mit den Lautäußerungen (z.B. Gesang und Rufe) vieler mariner Säugetiere.

Marine Säuger sind in hohem Maße auf ihr Gehör angewiesen. Die Fähigkeit ihre Umgebung akustisch wahrzunehmen ist lebenswichtig. Anthropogen verursachter Unterwasserlärm kann Kommunikationssignale, sowie Räuber-, Beute- und Umgebungsgeräusche, die für das Tier wichtig sind, beeinflussen und dadurch die Fähigkeit des Tieres, diese biologisch wichtigen Geräusche zu empfangen, maskieren (Erbe 2000; Clark et al. 2009). Die potentiell schädliche Wirkung von Airguns (z.B. physische Schäden, Verhaltensänderungen) über kurze Distanzen von wenigen dutzenden Kilometern wird bereits seit einiger Zeit diskutiert (Gordon et al. 1998; Yazvenko et al. 2007; Erbe & King 2009; Breitzke & Bohlen 2010; Gray & Van Waerebeek 2011). Die Fernwirkung von akustischer Maskierung wurde bisher nur teilweise in wissenschaftlichen Untersuchungen und Umweltprüfungen berücksichtigt. Nur wenige Studien haben die möglichen schädlichen Auswirkung auf marine Säuger, die Maskierung durch die Nutzung von Airguns hervorrufen kann, beurteilt (Streever et al. 2012).

Airgun-Signale können unter Wasser über weite Distanzen lauter als die natürlichen Hintergrundgeräusche wahrgenommen werden. Während der Schallausbreitung werden die Impulse an der Oberfläche mehrfach reflektiert und in Schallkanälen gebrochen (Urick 1983). Bedingt durch diese Prozesse ändern sich über lange Distanzen die spektralen Anteile und die Länge der empfangenen Zeitsignale (Signaldehnung). Durch diese Effekte der unterschiedlichen Schallausbreitung kann sich der ursprünglich impulsartige Schall der Airgun zu einem kontinuierlichen Geräusch entwickeln, und hierdurch zu einem allgemeinen Anstieg des Hintergrundrauschens führen, was zur Folge haben kann, dass auch die Zeit zwischen einzelnen Airgunschüssen durch kontinuierliches Rauschen beschallt wird. Liegen die empfangenen Signale über der Hörschwelle mariner Säugetiere, kann ein kontinuierlicher Maskierungseffekt eintreten.

Der Antarktische Kontinent und das Südpolarmeer südlich von 60°S sind durch den Antarktisvertrag (AV) besonders geschützt. Die Ergänzungen des Umweltschutzprotokolls zum AV stellen insbesondere auch marine Säugetiere unter diesen besonderen Schutz. In Deutschland wurde das Protokoll durch das AUG[2] in deutsches Recht umgesetzt. Genehmigungen werden durch das Umweltbundesamt (UBA) ausgestellt.

Die wissenschaftliche Basis zur Abschätzung der durch Airguns ausgelösten Umweltwirkungen auf die Schutzgüter der Antarktis ist noch durch Wissenslücken geprägt. Insbesondere eine Maskierung der Lautäußerungen und ein damit einhergehendes Unvermögen in verschiedenen Ge-

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[2] Gesetz zur Ausführung des Umweltschutzprotokolls vom 4. Oktober 1991 zum Antarktis-Vertrag (Umweltschutzprotokoll-Ausführungsgesetz) vom 22. September 1994 (BGBl. I S. 2593),

räuschkulissen zu kommunizieren kann nachteilige Auswirkungen haben. Potentielle Effekte sind unter anderem der Verlust der Fähigkeit zur gemeinschaftlichen Jagd, Kontaktverlust zwischen Mutter und Kalb und vor allem der Verlust an Möglichkeiten einen Fortpflanzungspartner zu finden. Sollte diese Kommunikation nachhaltig maskiert sein, ist davon auszugehen dass ein Populationseffekt eintritt.

Das Ziel dieses Projektes ist die Evaluierung potentieller Auswirkungen der wissenschaftlichen Nutzung von Airguns in der Antarktis.

Methodik

Die Evaluation, ob potentielle Maskierungseffekte vorhanden sind, wurde in drei Schritten durchgeführt. Zuerst wurde eine Literaturrecherche über die betroffenen Arten, ihre Vokalisation, mögliche geografische und zeitliche Überlappungen der Arten mit der wissenschaftlichen Nutzung von Airguns und Überschneidungen im Frequenzgehalt der Airgunsignale und der Vokalisation der vorkommenden Tiere durchgeführt. Der zweite Schritt beinhaltete die Modellierung der Schallausbreitung und im dritten Schritt wurde die Modellierung der Maskierungseffekte vorgenommen.

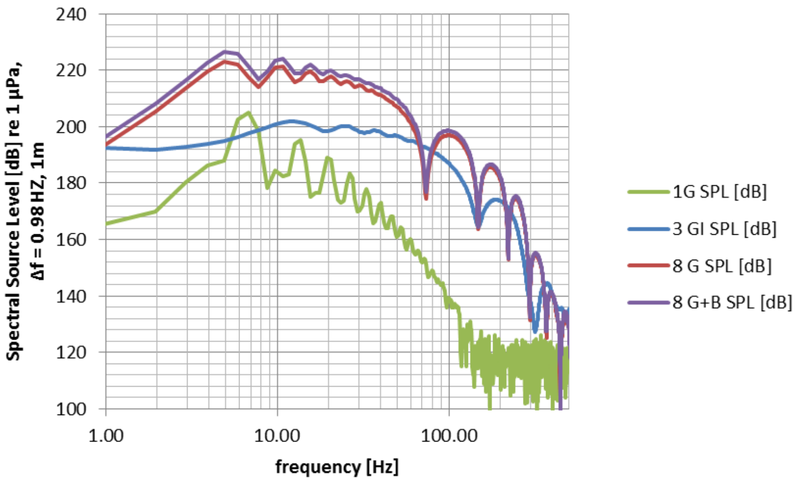
Literaturrecherche

Im Zuge dieser Arbeit wurde eine umfassende Literaturrecherche zur Verbreitung, der Abundanz und den Vokalisationen der südlich von 60°S vorkommenden marinen Säugetiere vorgenommen. Die Ergebnisse sind im nachfolgenden Bericht zusammengefasst, würden allerdings den Rahmen dieser Zusammenfassung überschreiten. Basierend auf der Recherche wurden drei Arten für die weitere Modellierung gewählt: Blauwal (*Balaenoptera* musculus), Finnwal (*Balaenoptera* physalus) und Weddellrobbe (*Leptonychotes Weddellii*). Für die ausgewählten Arten wurden Daten ihrer Vokalisationen (Z-calls für Blauwale, 20 Hz Pulse für Finnwale und drei Weddellrobbenvokalisationen) gesammelt und für die Modellierung der Maskierung genutzt.

Modellierung der Schallausbreitung

Die Modellierung der Schallausbreitung wurde für Empfängerpositionen in 100, 500, 1000 und 2000 km Distanz von der Schallquelle und für Wassertiefen von 500 und 4000 m (flacher Ozeanboden) auf der Grundlage der gemessenen Schallgeschwindigkeitsprofile durchgeführt. Als dritte Variable wurde die Empfängertiefe (10, 50 und 200 m) betrachtet. Das Zeitsignal der Airgun-Impulse wurde aus einer früheren Studie mit einer bei seismischen Explorationen üblichen Airgunposition von 10 m Sendertiefe (theoretische Signatur) entnommen und dann anhand einer Fast Fourier Transformation (FFT) in ein Frequenzspektrum umgewandelt (Abb. 2-1). Das Signal wurde dann mit AcTUP (*Acoustic* T*oolbox* U*ser-interface &* P*ostprocessor*) verarbeitet, um den Ausbreitungsverlust (Transmission Loss; TL) abzuschätzen. Die inverse FFT des empfangenen Signals wurde genutzt, um das Zeitsignal des empfangenen Airgun-Impulses zu rekonstruieren. Für die vorgenommenen Analysen wurde ein *mode summation* Algorithmus genutzt, welcher ähnliche Ergebnisse wie eine parabolische Gleichung erzeugte, aber weniger Rechenzeit erforderte. Dämpfung wurde nicht berücksichtigt. Die Ergebnisse können daher als ein Maximum für die entsprechende Konfiguration (Sender, Empfängertiefe und Schallgeschwindigkeit) angesehen werden.

Abb. 2-1 Frequenzspektren für die Zeitsignale der in Betracht gezogenen Airgun-Konfigurationen. Für die Modellierung des Maskierungseffektes wurde nur die 8 G Konfiguration (8 G—Airguns mit je 8.5 L Kammervolumen) betrachtet. 1 G – 1 G-Airgun mit 8,5 L, 3 GI – 3 GI-Airguns mit je 2,4 L, 8 G+B – 8 G-Airguns mit je 8,5 L und 1 Bolt PAR CT800 Airgun mit 32,8 L.



Modellierung der Maskierungseffekte

Um die Anzahl der notwendigen Berechnungen zu reduzieren wurden die Analysen auf die in der Literaturrecherche identifizierten Modellarten Blauwal, Finnwal und Weddellrobbe beschränkt.

Um die impulshafte Natur der Airgun-Signale in verschiedenen Entfernungen und Wassertiefen zu berücksichtigen, war es notwendig zu prüfen, ob die Kommunikationssignale der Tiere während der Nutzung der Airguns detektiert werden können. Zur Beschreibung der Hörprozesse der Wale und Robben wurde ein Modell herangezogen, das einen „*leaky integrator*" (Integrator, der einen konstanten Anteil an Energie pro festgelegter Zeiteinheit verliert) mit einem Pegeldetektor (*level detector)* kombiniert. Dieses einfache Modell wurde gewählt, da zurzeit nur wenige Detailkenntnisse über das Gehör von Bartenwalen existieren. Bezogen auf die Hörschwelle wurde angenommen, dass Bartenwale und Robben *noise limited* sind und somit alle Signale in den modellierten tiefen Frequenzen, die lauter als das natürliche Hintergrundrauschen sind, hören. Natürliches Hintergrundrauschen wird angenommen für Seegang des Status 3-4 gemäß Wenz-Kurven (Wenz, 1962)). Das in dieser Modellierung verwendete Rauschen war tatsächliches Hintergrundrauschen aufgenommen auf See und skaliert auf 80 dB re µPa rms).

Die Maskierungs-Modellierung beinhaltet folgende Schritte:

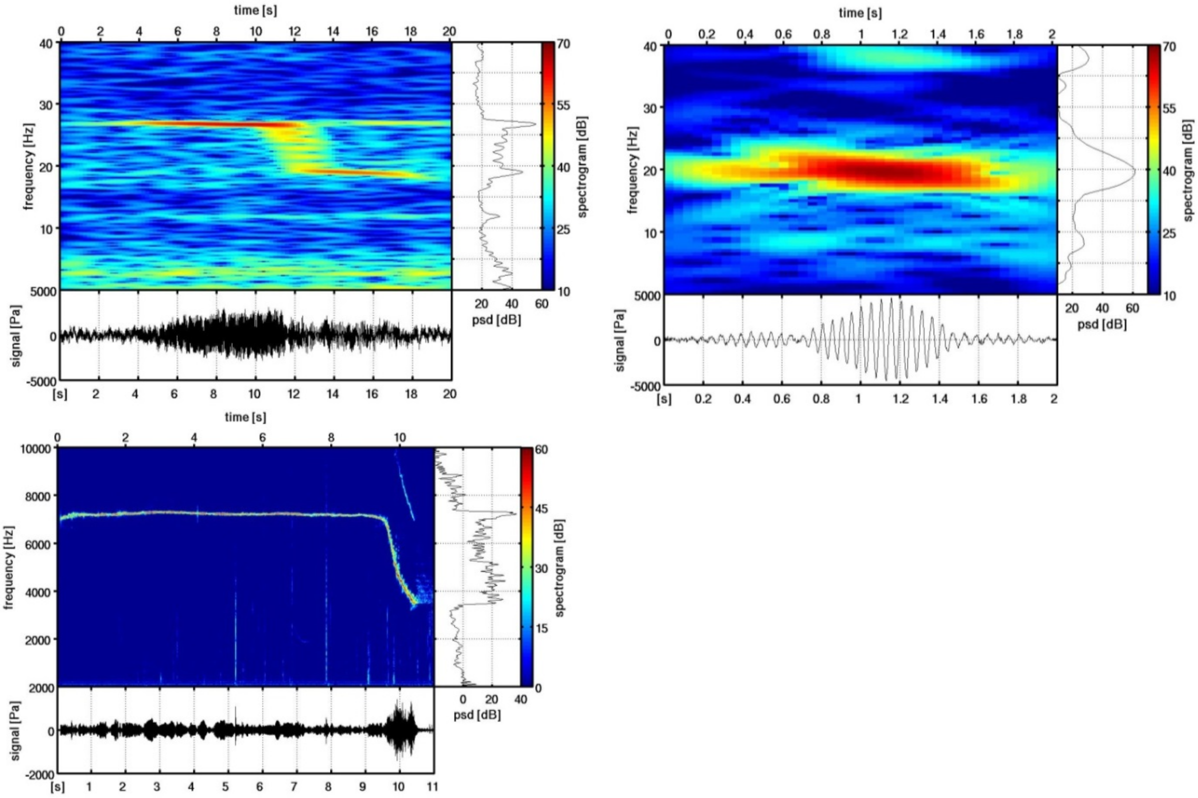
Das empfangene Signal der Airgun und das Hintergrundrauschen wurden überlagert und der *leaky integrator* (LI) wurde erst auf das Hintergrundrauschen allein angewendet, um die Detektionsschwellen bezogen auf das Hintergrundrauschen abzuschätzen (natürlicher Zustand). Anschließend wurde der LI auf das Airgun-Signal, überlagert mit dem Hintergundrauschen, angewendet (maskierter Zustand). Alle Signale wurden Bandpass-gefiltert (angepasst auf den Frequenzbereich der Tiervokalisationen, siehe nachfolgend).

- Tiervokalisationen (Abb. 2-2) wurden
    - den verfügbaren Aufnahmen entnommen, skaliert auf die in der Literatur angegebenen Quellschallpegel, Dauer und Frequenzbereich wurden den tatsächlichen Aufnahmen entnommen, und
    - mit einem Bandpassfilter gefiltert

- Ein leaky integrator wurde definiert bei dem die gesamte Dauer des Signals als Zeitkonstante genutzt wurde (Fall der bestmöglichen Detektion) und
- In einem zweiten Schritt wurde die Zeitkonstante des *leaky integrators* als 0,2 s definiert, um die aus der Literatur bekannten physiologischen Werte für Säugetiere angemessener zu repräsentieren (Kastelein et al. 2010).
- Die leaky integrator Ausgaben wurden verglichen und Maskierungsdistanzen berechnet. Beispiele für Spektrogramme der genutzten Signale sind in Abb. 2-2 dargestellt.
- Es ist nicht bekannt ob die Tiere die volle Länge der Signale benötigen um die Vokalisation ihrer Artgenossen detektieren. Um festzustellen ob sich die Ergebnisse grundlegend ändern, wenn unterschiedliche Anteile des Signals für eine Detektion nötig sind, wurde eine entsprechende Sensitivitätsanalyse durchgeführt.

Quellschallpegel der Tiervokalisationen wurden der Literatur entnommen. Für Blauwale wurden 179 dB re µPa m, (Samaran et al. 2010a) und für Finnwale 189 dB re µPa m (Širović et al. 2007) ermittelt. Für Weddellrobben wurde der Mittelwert der bisher verfügbaren Werte mit 173 dB re µPa m (Thomas and Kuechel 1982; Thomas et al., 1983b; Thomas and Stirling 1983) als Schätzwert angenommen.

Abb. 2-2 Zur Modellierung genutzte Eingangssignale (oben links: Blauwal, oben rechts: Finnwal, unten links: Weddellrobbe).



Die Tiervokalisationen wurden dem Quellschallpegel angepasst und mit einem Bandpassfilter gefiltert um der Bandbreite der Vokalisationen gerecht zu werden. Die verbreiteten Airgunsignale wurden in der gleichen Weise gefiltert und die Ergebnisse des *leaky integrator* mit den berechneten Maskierungsdistanzen verglichen. psd – power spectral density (Schallleistungsdichte), das Spektrogramm zeigt den Frequenzgehalt des Signals über die Zeit, unterschiedliche Farbwerte zeigen dabei die Lautstärke des Signals als dB-Wert an (siehe Skala rechts).

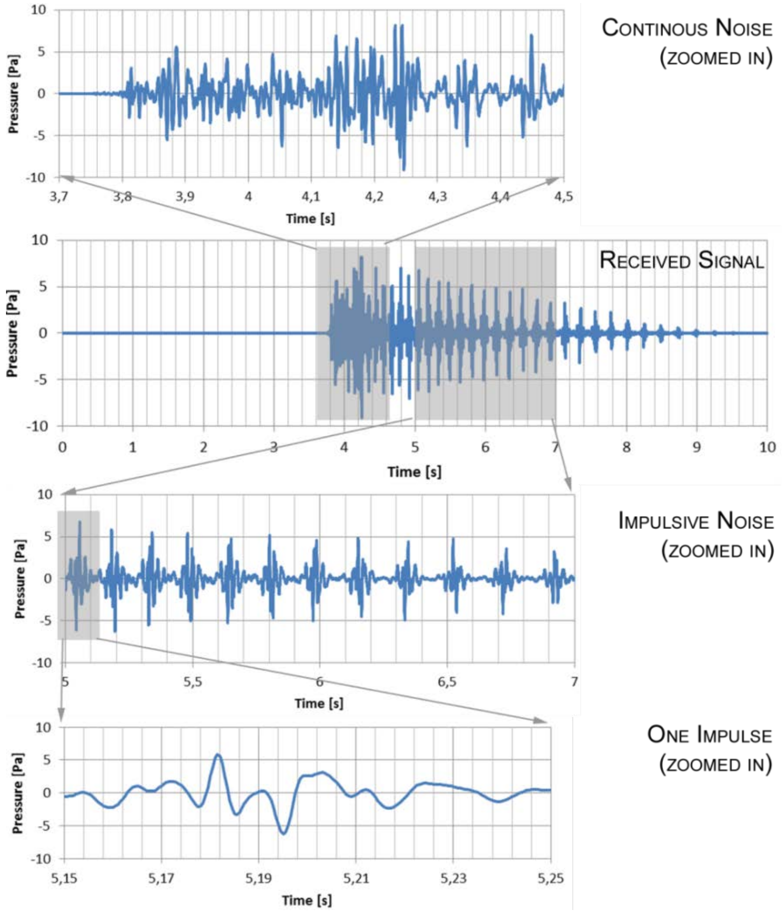
Ergebnisse

Modellierung der Schallausbreitung

Die Ergebnisse belegen, dass wenig der empfangenen Schallenergie aus den Signalenanteilen über 300 Hz resultiert. Die Modelle demonstrieren eine signifikante zeitliche Ausdehnung der Signale, die zu einem kontinuierlichem Geräusch zwischen 1000 und 2000 km Distanz von der Airgun führen kann.

In Abb. 2-3 ist ein Impuls in 100 km Entfernung von der Airgun beispielhaft dargestellt. Das Zeitsignal ist auf nahezu 6 Sekunden gedehnt, während die empfangenen spektralen Pegel immer noch 60 dB über dem Hintergrundrauschen liegen. Bei diesen Distanzen, ausgehend von einem Schussintervall von 15 s, entsteht also kein kontinuierliches Signal. Trotzdem wäre schon in dieser Distanz ein signifikanter Anteil der zu Verfügung stehenden Kommunikationszeit durch das gedehnte Airgunsignal überlagert und könnte daher bereits maskiert sein.

Abb. 2-3 Detaillierte Ansicht eines empfangenen Signals (in 100 km Distanz zur seismischen Aktivität) welches kontinuierlich fluktuierende und impulhafte Anteile beinhaltet.



Durch die *Modendispersion* (Ausbreitung auf verschiedenen Schallpfaden) nehmen Signale verschiedene Verbreitungswege mit unterschiedlicher Laufzeit und kommen somit zu verschiedenen Zeiten beim Empfänger an. Das Signal enthält dann impulshafte (multiple Reflektionen) sowie kontinuierliche Signalanteile.

Eine umfassendere Übersicht über die Ergebnisse der Schallausbreitungsmodellierung ist in Abb. 2-4 und Abb. 2-5 für tiefe Gewässer (4000 m Wassertiefe) dargestellt. Sie zeigt eine starke Dehnung des Signals, welches eine vollkommende Abdeckung des Zeitintervalls zwischen zwei aufeinanderfolgenden Airgun-Impulsen in 2000 km Distanz aufweist.

Abb. 2-4 Eingangssignal (Airgun) für die Maskierungsmodellierung für tiefe Gewässer (4000 m Tiefe), rd: Empfängertiefe, d: Distanz des modellierten Impulses der Airgun (8-G array mit je 8,5 l Volumen). Drei Impulse sind zu sehen, um zu zeigen wie der Anfang und das Ende der Sequenzen aussehen würden. Nur der mittlere Impuls wurde vervielfältigt und für die weiteren Berechnungen genutzt.

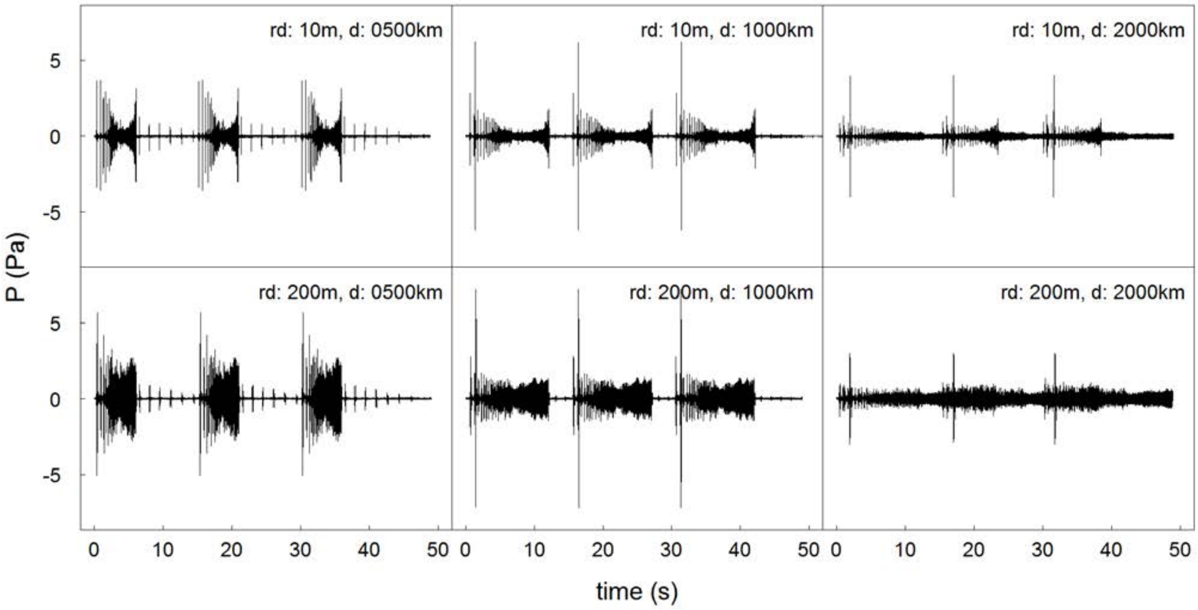
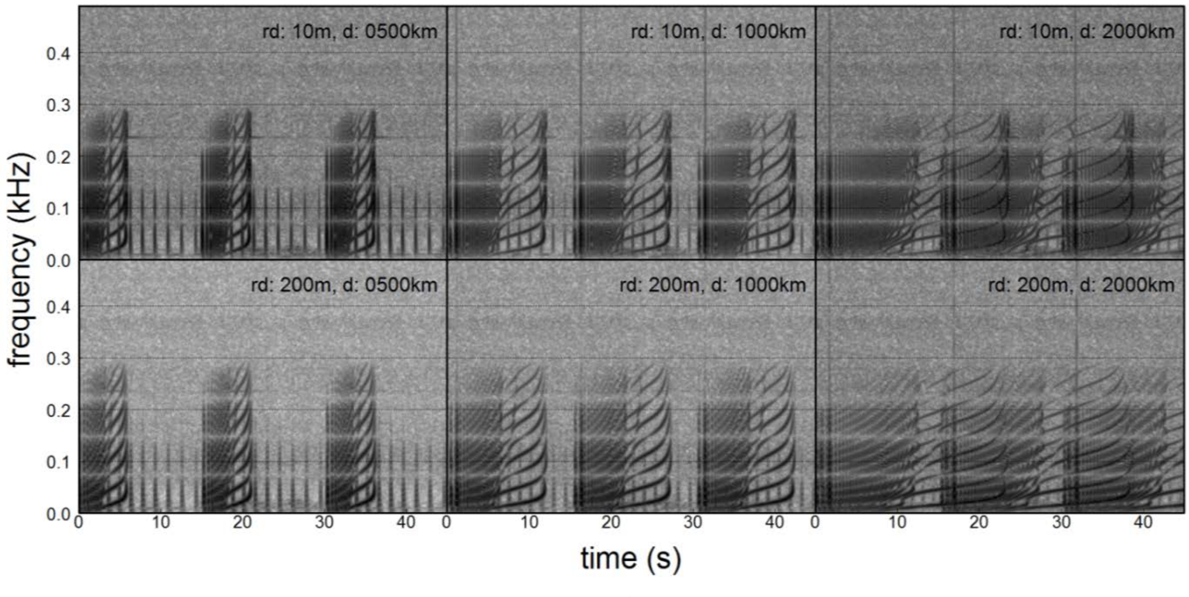


Abb. 2-5 Spektrogramme des Eingangssignals (Airgun) für die Maskierungsmodellierung für tiefe Gewässer (4000 m Tiefe), rd: Empfängertiefe, d: Distanz des modellierten Impulses des Airguns, 8-G array mit je 8,5 L Kammervolumen.



Es sind drei Impulse sind zu sehen, um zu zeigen wie der Anfang und das Ende der Sequenzen aussehen würden. Nur der mittlere Impuls wurde vervielfältigt und für die weiteren Berechnungen genutzt. Die Spektrogramme zeigen, dass die Signale tonale Frequenzen besitzen, folglich reicht ein Breitbandpegel für eine Berechnung der Maskierung nicht aus. Die Überschneidung des Frequenzbereichs mit der Tiervokalisation ist somit ausschlaggebend sollte eine Maskierung wirklich auftreten.

In flacheren Gewässern (500 m Wassertiefe) ist kein lineares Verhältnis zwischen Signaldehnung und Distanz feststellbar - die Dehnung ist aber immer noch beträchtlich. Der Wechsel von einem intervallartigen Geräusch (Wechsel zwischen kontinuierlichen, impulsartigen und unverlärmten Sequenzen) zu einem kontinuierlichen Signal findet vermutlich zwischen 1000 und 2000 km statt. Im Zuge dieses Projektes wurde auch die Möglichkeit eines Maskierungseffektes bei Signalen mit intervallartigem Charakter überprüft.

Die Frequenzspektren der empfangenen Zeitsignale (Beispiele in Abb. 2-5) zeigen, dass die Signale starke Tonabfolgen (*sweeps*) als entweder höher-werdende *upsweeps* in Tiefseekonditionen aber teilweise auch *downsweeps* (in der Frequenz abfallende Tonabfolgen) in flachen Gebieten enthalten. Die Impulse können sich überlagern und dadurch sinkt der Spitzenpegel im Gegensatz zu den mittleren Schallpegeln (rms) nicht zwangsläufig mit der Distanz.

Modellierung der Maskierung

18 Fälle mit verschiedenen Szenarien wurden im Hinblick auf die Wassertiefe, die Empfängertiefe und die Distanz zur Airgun modelliert. Um ein relatives Maß für Maskierung zu erhalten, wurde das Verhältnis zwischen der Distanz, wenn nur Hintergrundgeräusche präsent waren (natürliche Kommunikationsreichweite) und den Einzeldistanzen für jeden Fall und jede Art (maskierte Konditionen) herangezogen

Die Resultate zeigen, dass die Kommunikationsdistanzen für alle drei berücksichtigten Arten in Entfernungen zwischen 500 – 2000 km reduziert werden, allerdings ist dieser Effekt stark von der Frequenz der berücksichtigten Vokalisation abhängig. Zum Beispiel wurde für die drei getesteten Weddellrobben-Vokalisationen festgestellt, dass das geschätzte Maskierungspotential hoch variabel ist und die maskierte Kommunikationsdistanz zwischen 92 % (nahezu keine Maskierung) und 1 % der potentiell ungestörten Kommunikationsreichweite schwankt (siehe Table 1 – 1 für Details der Kommunikationsdistanzen). Für Blau- und Finnwale liegt der modellierte Verlust an Kommunikationsreichweite stets im Bereich von ein bis zwei Zehnerpotenzen (90-99 % Verlust an Kommunikationsreichweite).

Kommunikationsreichweiten für Blau- und Finnwale werden drastisch reduziert, allerdings sinkt der Effekt nicht kontinuierlich mit der zunehmender Entfernung was vermuten lässt, dass Maskierung sowohl bei impulshaften Geräuschen als auch bei kontinuierlichem Schall auftreten kann. Die Ergebnisse für die Weddellrobben sind hoch variabel und zeigen kein klares Muster. Zusätzlich wurde die Vokalisation der Weddellrobbe mit zwei verschiedenen Bandpassfiltern gefiltert: Reicht der hochfrequente Anteil des Signals (mit höherer Energie im Vergleich zu den tiefen Frequenzen) für eine Detektion aus, führt dies zu einer Reduzierung des Maskierungspotentials durch die Störsignale. Um solche Erkenntnisse für Arten, die einen breiten Frequenzbereich in ihren Vokalisationen abdecken, in die Modellierung einfließen zu lassen, ist es nötig ein besseres Verständnis der Hörprozesse zu erreichen, um die potentiellen Auswirkungen von Maskierung besser abschätzen zu können.

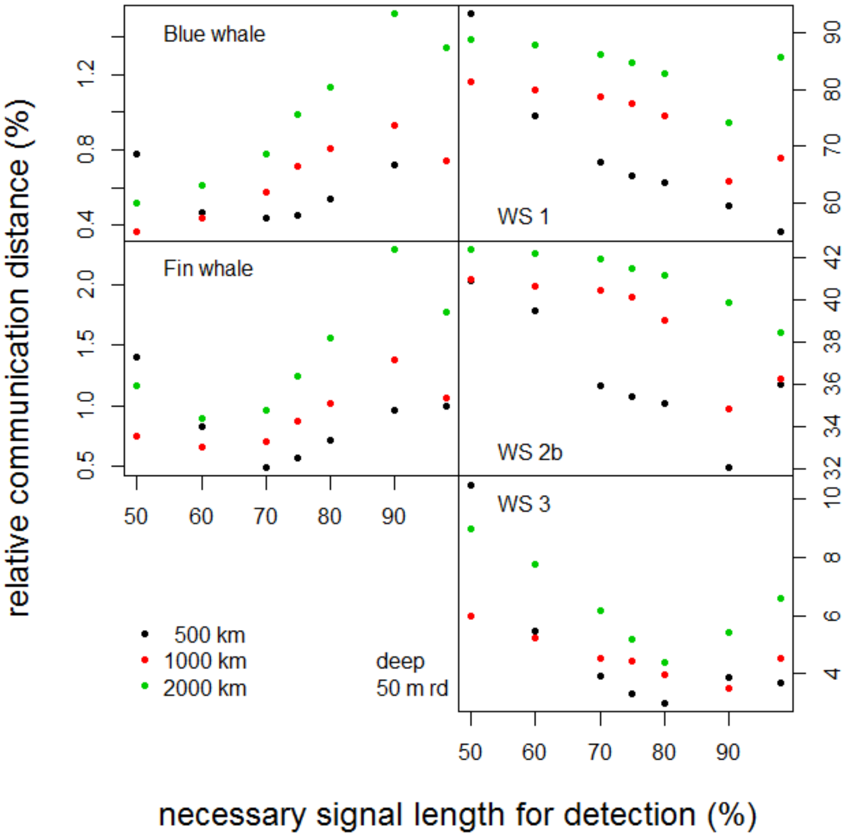
Tab. 2-1 Akustische Kommunikationsdistanzen für fünf berücksichtigte Vokalisationen.

Fall	Empfängertiefe	Distanz Airgun - Empfänger	Wassertiefe	Relativer Verlust an akustischer Kommunikationsdistanz (Verhältnis von natürlicher und maskierter Kommunikationsreichweite [%])					
				Blauwal	Finnwal	Weddellrobbe			
						#1	#2a	#2b	#3
1	10	500	tief 4000 m	97.7%	96.2%	97.7%	98.5%	65.8%	99.1%
2	10	1000		97.8%	95.9%	97.8%	97.7%	82.9%	99.2%
3	10	2000		95.8%	91.5%	95.8%	96.5%	76.7%	98.6%
4	50	500		99.3%	98.9%	99.3%	98.4%	82.1%	99.4%
5	50	1000		99.3%	98.9%	99.3%	97.6%	77.7%	99.1%
6	50	2000		98.6%	97.7%	98.6%	96.2%	70.1%	98.7%
7	200	500		99.2%	99.0%	99.2%	96.4%	75.0%	98.5%
8	200	1000		99.0%	98.7%	99.0%	94.3%	77.7%	98.8%
9	200	2000		97.9%	97.3%	97.9%	91.8%	75.7%	98.0%
10	10	500	flach 500 m	96.6%	95.0%	96.6%	98.5%	62.0%	99.1%
11	10	1000		93.2%	90.4%	93.2%	97.8%	60.3%	98.6%
12	10	2000		88.8%	82.0%	88.8%	96.4%	59.9%	97.7%
13	50	500		99.2%	98.9%	99.2%	98.5%	82.9%	99.5%
14	50	1000		98.5%	97.8%	98.5%	97.7%	75.2%	99.2%
15	50	2000		97.3%	96.0%	97.3%	96.1%	66.6%	98.7%
16	200	500		99.3%	99.3%	99.3%	96.6%	74.8%	98.6%
17	200	1000		98.5%	98.5%	98.5%	93.2%	65.0%	97.1%
18	200	2000		97.1%	96.8%	97.1%	87.0%	60.3%	94.2%

Sphärische Ausbreitung wurde genutzt um die Schallausbreitung der Vokalisationen zu modellieren; Annahmen: Zeitkonstante (TC): 200 ms, Meerwasserdämpfung und 100 % freie Kommunikationszeit für eine Detektion. Diese Tabelle dient als Beispiel für die Ergebnisse. Verschiedene Szenarios wurden in Betracht gezogen und die Ergebnisse sind im Anhang zusammengefasst.

Innerhalb dieser Studie wurde angenommen, dass die Tiere das vollständige Signal unmaskiert wahrnehmen müssen, um es detektieren zu können. Signale von Bartenwalen sind jedoch lang und deshalb besteht die Möglichkeit, dass sie nicht die volle Signallänge für eine Detektion benötigen. Um zu überprüfen, ob diese Annahme (dass die volle Signallänge notwendig ist) einen großen Einfluss auf die Ergebnisse hat, führten wir eine Sensitivitätsanalyse durch: Abb. 2-6 zeigt die relative Kommunikationsdistanz (Reichweite unter maskierten Bedingungen relativ zur natürlichen Reichweite), unter der Annahme, dass die Tiere nicht die volle Signallänge benötigen, um die Vokalisation ihrer Artgenossen zu detektieren. Die Sensitivitätsanalyse zeigt, dass sich zwar die Maskierungsreichweite mit der (für eine Detektion benötigten) Signallänge ändert, die Größenordnung des Effektes aber gleich bleibt. Dies gilt selbst unter der Annahme dass die benötigte Signallänge für eine Detektion nur 50 % anstatt von 100 % ist und die Tiere somit eine deutlich kürzere Zeit zum detektieren des Signals ihrer Artgenossen benötigen. Die Empfängertiefe, als eine Eingangsvariable, ändert diese Ergebnisse ebenfalls nicht in erheblichem Maße.

Abb. 2-6 Notwendige Signallänge für eine Detektion gegenüber der verfügbaren relativen Kommunikationsdistanz (Verhältnis zwischen maskierter und natürlicher Kommunikationsdistanz, als relatives Maß für den Verlust an Kommunikationsreichweite). Obwohl die notwendige Signallänge für eine Detektion zwischen 50 und 100 % verändert wurde, ändert sich das Maskierungspotential nur geringfügig.



Für eine Empfängertiefe von **50 m**, Ausbreitungsmodell für tiefe Bedingungen (4.000 m Wassertiefe) und die getesteten Signale. WS-Weddellrobbe. Während das Maskierungspotential (hier ausgedrückt als relativ vorhandene Kommunikationsreichweite unter Airguneinsatz im Vergleich zur natürlichen Kommunikationsreichweite) sich mit abnehmender Distanz zum Airgunarray verringert, sind trotzdem die Größenordnungen vergleichbar, obwohl die notwendige Signallänge für eine Detektion stark variiert wurde: Finn- und Blauwale haben ca. 0,4 bis 2 % ihrer natürlichen Kommunikationsdistanz. Für Weddellrobben sind die Ergebnisse - abhängig vom getesteten Vokalisationstypen - aber viel variabler. Das Verhältnis ist demzufolge hochgradig abhängig von der Vokalisation der Tiere und kann somit nicht in einem vereinfachten Modell ausgedrückt werden. Graphen für alle Szenarien sind in Appendix C zu finden.

Diskussion

Mit großer Wahrscheinlichkeit gilt, dass

- die modellierten Ergebnisse korrekt sind: die modellierten empfangenen Signale sind vergleichbar mit realen empfangenen Signalen von Airgun-Impulsen.
- Airguns die Kommunikation von marinen Säugetieren bis in Distanzen von über 2000 km maskieren können. Dies gilt insbesondere für Tiere die hauptsächlich den oberen Bereich der Wassersäule (0-200 m) nutzen und relativ tieffrequent (< 100 Hz) vokalisieren.
- die Kommunikationsreichweiten für Finn- und Blauwale erheblich sinken.

- die Kommunikation von Tieren, die Frequenzbereiche > 300 Hz nutzen, nicht im gleichen Ausmaß betroffen sein wird.
- Robben wahrscheinlich weniger stark betroffen sind. Jedoch können die tieffrequenten Anteile ihrer Vokalisatione, die über weite Entfernungen tragen, von Maskierung betroffen sein.
- Maskierungseffekte in Regionen mit großen Wassertiefen wahrscheinlicher sind.
- Fluktuationen im Airgunsignal in mittleren Entfernungen (zwischen 500 – 1000 km) ein Signal mit einem intervallartigen (unterbrochenen) Charakter ausbilden.
- die Kommunikation von Blau- und Finnwalen selbst bei intervallartigen (unterbrochenen) Störsignalen stark maskiert wird, da die Ergebnisse der Maskierungsmodellierung nur unwesentlich durch die für die Detektion notwendige (angenommene) Signallänge beeinflußt werden. Aufgrund der ebenfalls vorhandenen Fluktuationen des Hintergrundrauschens erhöht sich durch diese Annahme sowohl die natürliche als auch die maskierte Kommunikationsreichweite. Das Verhältnis der Distanzen ändert sich jedoch kaum.

Die hier präsentierten Ergebnisse sind der erste Ansatz um den Verlust von akustischer Kommunikationsreichweite durch seismische Airguns vorherzusagen. Sind die Annahmen dieser Studie zutreffend, dann kann aus dem modellierten Verlust an Kommunikationsraum ein erheblicher Effekt auf individueller und Populationsebene resultieren.

Allerdings ist zu berücksichtigen, dass nur begrenzt Kenntnisse über das Hörvermögen von Bartenwalen bekannt sind und kaum empirische Daten zur Überprüfung der Schallausbreitung in den notwendigen Empfängertiefen und Bandbreiten vorliegen: Verfügbare Daten stammen überwiegend von Tiefseerekordern (also in Tiefen in denen Bartenwale nicht vorkommen) oder wurden nahe der Wasseroberfläche aber limiert in der Bandbreite aufgezeichnet.

Die Ergebnisse dieser Studie zeigen eindeutig, dass eine Beeinflussung im Sinne des Vorsorgeprinzips nicht ausgeschlossen werden kann. Allerdings sollte die Modelle mit empirischen Daten evaluiert werden, bevor die quantitativen Ergebnisse in einem Naturschutzkontext angewendet werden.

Insbesondere die modellierten Empfangspegel der Airgun-Signale haben starken Einfluss auf das Ergebnis des Maskierungsmodells und müssen als ‚*worst-case scenario*' in diese Studie angesehen werden. Die daraus resultierenden Maskierungsreichweiten stellen wahrscheinlich eine Überschätzung dar. Wesentliche Informationen über die Hörfähigkeiten von Bartenwalen, wie zum Beispiel der kritische Rauschabstand (Das Signal-Rausch-Verhältnis bei dem die Diskriminierung von Schallsignalen in Rauschen noch möglich ist.) und die Fähigkeit Schall aus verschiedenen Einfallswinkeln (s. u.) mit höherer Genauigkeit zu detektieren, werden sehr wahrscheinlich die Ergebnisse verändern.

Die Nutzung eines *leaky integrator* als Modell für die Detektion der empfangenen Signale, hat einige Erkenntnisse geliefert: Es konnten unterschiedliche Grade der Überdeckung der Vokalisation durch Airgunsignale betrachtet und weitere Parameter wie die Zeitkonstante der Integration angepasst werden.

Ein Nachteil ist allerdings, dass der *leaky integrator* (derzeitig) nicht die Fähigkeit von Tieren Signale aus verschiedenen Einfallswinkeln genauer wahrzunehmen (*directivity index*), darstellen kann: Marine Säugetiere können einschätzen, aus welcher Richtung ein Schallsignal kommt, so dass es mit größer werdendem Winkel zwischen zwei Schallquellen einfacher wird die beiden Quellen zu separieren. Es sind derzeit keinerlei Daten vorhanden die eine Vorhersage über das

Richtungshören von Bartenwalen ermöglichen. Diese Wissenslücke kann gegebenenfalls mit Hilfe von kontrollierten Expositionsexperimenten geschlossen werden.

Ein wichtiger Punkt, der in dieser Studie nicht berücksichtigt werden konnte, ist das passive Hören. Tiere ziehen Informationen über Beute, Predatoren und andere natürliche Schallereignisse aus der sie umgebenen Geräuschkulisse. Sollten diese Geräusche maskiert sein, können folgenschwere Auswirkungen auftreten. Jedoch können derzeit keine wissenschaftlich fundierten Annahmen getroffen werden, um diese Auswirkungen zu modellieren. Die Analysen dieser Studie wurden deshalb auf Fälle beschränkt, für die hinreichend belegbare Annahmen getroffen werden können.

Aus den Ergebnissen ist ersichtlich, dass weiterer Forschungsbedarf besteht. Die aktuellen Ergebnisse zeigen aber, dass Maskierungseffekte über große Distanzen und signifikante Auswirkungen auf das Vokalisationsverhalten von Tieren möglich sind und bei der Bewertung von Umweltwirkungen von impulshaften Schallquellen wie Airguns nicht außer Acht gelassen werden sollte.

3 Introduction

The use of impulsive sound sources such as airguns leads to considerable emission of acoustic energy into the oceans. This sound propagates over great distances and can have substantial effects on marine organisms. Negative effects have been shown for numerous species of marine organisms if they are exposed to this sound at relevant levels. These effects may range from stress, severe behavioural reactions, habitat loss, reduction of fitness as well as of the general health status, reduction of communication ability all the way to reversible and irreversible impairment of the auditory sense (and ultimately even to death).

The Antarctic continent and the Southern Ocean south of 60°S are specially protected under the Antarctic Treaty (AT). The annexes of the Environmental Protocol of the AT provide legislative protection expecially for marine mammals on individual level im terms of injury and disturbance. In Germany the act is legally implemented by the AIEP[3] and permits are issued by the German Federal Environment Agency (UBA). Currently, there are still considerable gaps in the scientific basis for assessing environmental effects induced by the use of airguns on Antarctic marine mammals that are specially protected under the Protocol on Environmental Protection to the AT. Specifically masking of communication sounds, the inability to communicate in different noise conditions, may have detrimental effects. Potential effects include amongst others the loss of the ability to feed cooperatively, to keep contact between mother and calf, but most importantly finding partners for mating. If these communications are masked to a high degree, it is feasible that population level effects occur. These effects must be considered when the precautionary principle is applied.

There are currently wide gaps in the existing knowledge of vocalisations (and their functions) of marine mammals, which hamper statements specifically regarding acoustic masking. Despite significant uncertainties, potentially detrimental effects of masking should be considered in different scenarios on the basis of current scientific knowledge within this project.

For the evaluation, whether masking occurs and is potentially detrimental, we conducted sound propagation modelling of airgun impulses to estimate how the signal in its time and frequency domain is received in different distances from the seismic source. Furthermore signals of blue whales (*Balaenoptera musculus intermedia*), fin whales (*Balaenoptera physalus*) and Weddell seals (*Leptonychotes Weddellii*) were overlaid with the received airgun impulses to estimate in which distances the animals are able to hear conspecific vocalisations under these disturbed conditions.

3.1 Protection of the Antarctic region and species

The Antarctic Treaty as the international basis for the peaceful use of the Antarctic Ocean south of 60°S latitude defines that the 50 current member states are obliged to follow regulations defined within the Antarctic Treaty System (ATS). In addition to the AT itself, the ATS also comprises the Protocol on Environmental Protection to the Antarctic Treaty (or short Environmental Protocol -EP), the Convention for the Conservation of Antarctic Marine Living Resources (CCAMLR) and the Convention for the Conservation of Antarctic Seals (CCAS). The Act Imple-

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[3] German Act Implementing the Protocol on Environmental Protection of 4 October 1991 to the Antarctic Treaty (AIEP); In German: Gesetz zur Ausführung des Umweltschutzprotokolls vom 4. Oktober 1991 zum Antarktis-Vertrag (Umweltschutzprotokoll-Ausführungsgesetz);

menting the Protocol of Environmental Protection (AIEP)[4] transposes the EP into German law and makes all activities that are organised in Germany or originate within its sovereign territory subject to a permit by the German Federal Environment Agency. Amongst other obligations a licence can only be obtained if there are no detrimental changes in the distribution, abundance or productivity of species or populations of species of fauna and flora. Furthermore there shall be no introduction of further jeopardy to endangered or threatened species or populations of such species according to the Environmental Protocol.

The ATS provides protection on population level for marine mammals, penguins und other birds within the sensitive ecosystem around Antarctica. In the future, invertebrates (such as krill and cephalopods) will be covered by the same degree of protection under the Environmental Protocol[5].

The ATS furthermore provides protection on individual level for all native species of marine mammals and birds including those which occur only seasonally due to natural migrations. Furthermore the protection of natural habitats is a primary objective. This includes from our perspective habitat loss by displacement effects (due to avoidance of seismic activities) in marine mammals as well loss of habitat quality by displacement effects in their prey species and a possible reduction in acoustic communication ranges in both groups.

For cetaceans the regulatory body for management and conservation is the International Whaling Commission (IWC). The IWC "...provide[s] for the proper conservation of whale stocks and thus make[s] possible the orderly development of the whaling industry." (IWC 1946). The IWC undertakes annual surveys south of 60°S in austral summer. The Antarctic is also protected within the Southern Ocean Whale Sanctuary (SOWS, adopted by the IWC in 1994, Fig. 3-1 and Fig. 3-2). The SOWS boundaries are the Indian Ocean Sanctuary, south of 60°s around South America and in the South Pacific and 40°S for the remaining areas (Gill and Evans, 2002). Research on seals is specifically coordinated by the Group of Specialists on Seals within the Scientific Committee on Antarctic Research (SCAR).

Species of the Antarctic region are listed in the International Union for Conservation of Nature (IUCN) Red List categories. Data of the current Red List have been taken into account for species profiles and have to be regarded as expert opinion about necessary protection for a more global perspective.

This report focuses on native species in Antarctica based on the protection of individuals within the ATS. However when a methodology has been shown to be able to predict consequences on population level this approach might have to be widened to other areas with different species. The status under the IUCN will be considered, but will not be a primary focus, as the EP protects all native mammals irrespective of their conservation status in the IUCN Red List. Additional protection is expressed in Appendix I of the Convention on the Conservation of Migratory Species of Wild Animals (CMS) defining a strict protection of the listed species while Appendix II places emphasis on species requiring international collaboration for conservation tasks. The Convention on International Trade in Endangered Species (CITES) furthermore aims at regulating international trade of threatened species and populations.

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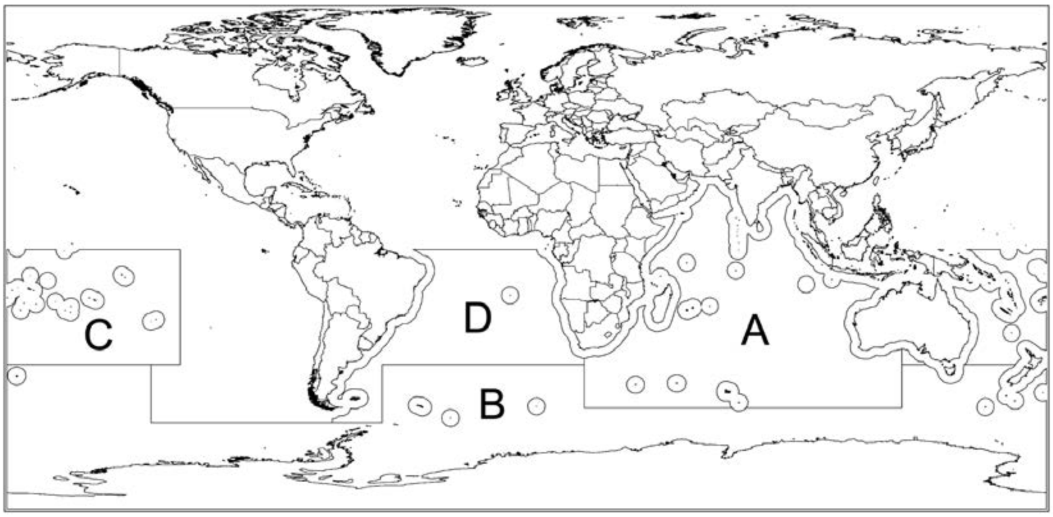
[4] Act implementing the Protocol of Environmental Protection of 4 October 1991 to the Antarctic Treaty (AIEP), BGBl. II 1994, 2478; entered into force on 14 January 1998.

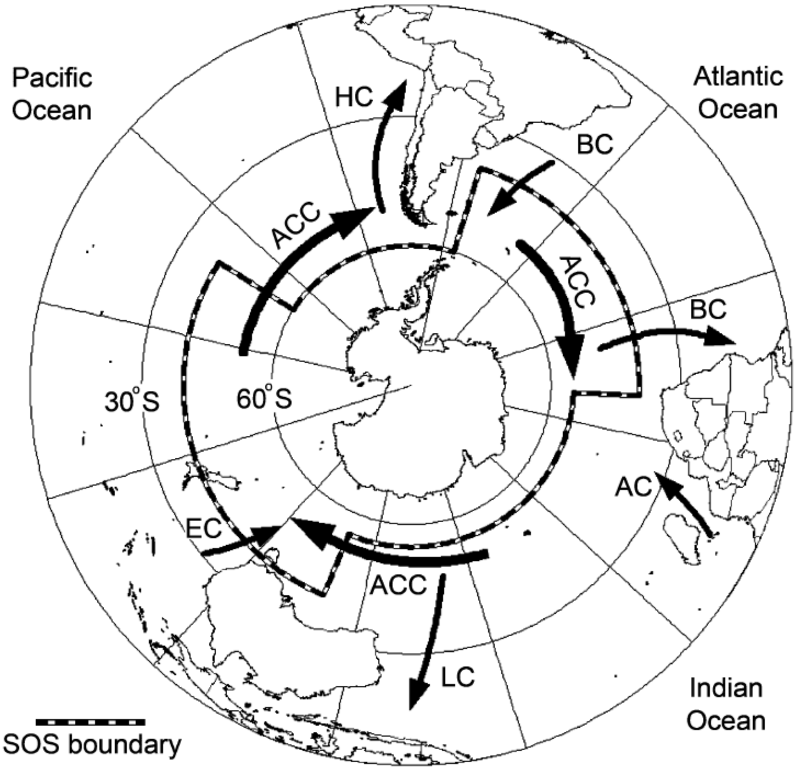
[5] Cf. amended version of Annex II to the Environmental Protocol, Measure 16 (2009)

Fig. 3-1 IWC Sanctuaries



(A) Indian and (B) Southern Ocean. The (C) South pacific and (D) South Atlantic were not adopted at the 56th IWC meeting, Sorrento, Italy (taken from Zacharius et al. 2006)

Fig. 3-2 The Southern Ocean Whale Sanctuary (SOWS, dashed line) and major oceanographic fluxes



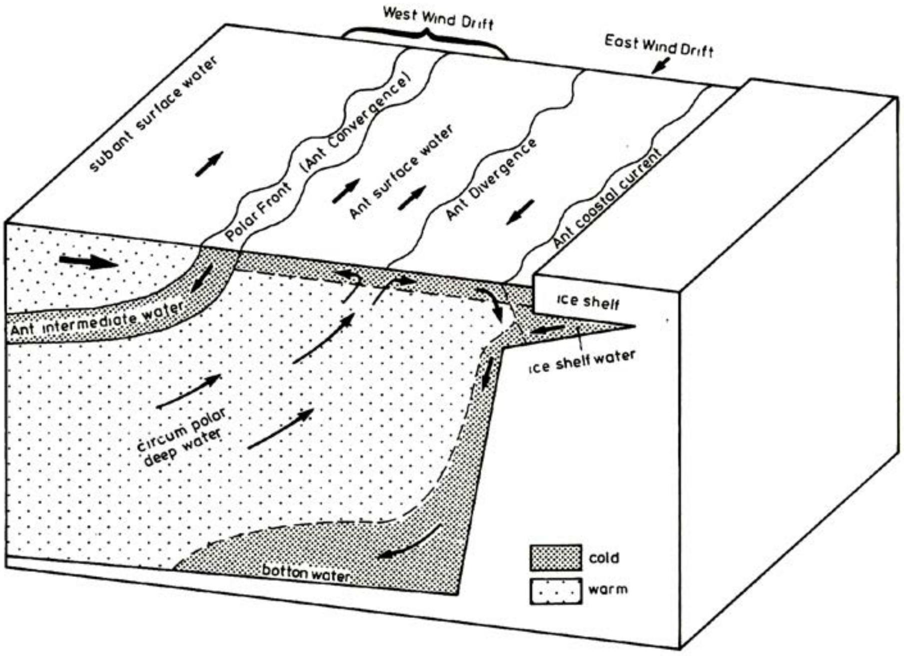
ACC -Antarctic Circumpolar Current, BC - Benguela Current, HC – Humboldt Current, LC – Leeuwin Current, BC – Brazil Current, EC – East Australia Current, AC – Agulhas Current (taken from Zacharius et al. 2006).

3.2 Study Area

According to Hempel (1985) the Antarctic ecosystem can be divided into three large latitudinal zones which are partly under large influences of seasonal changes (Fig. 3-3):

- Areas exposed to the west wind drift and hence are nearly ice-free throughout the year
- Areas exposed to the east wind drift having seasonally varying ice coverage, and
- Shelf waters with full ice cover for nearly the whole year, including stretches of open water enclosed by ice and open basins that may be covered with a layer of thin ice.

Fig. 3-3 The Antarctic current system

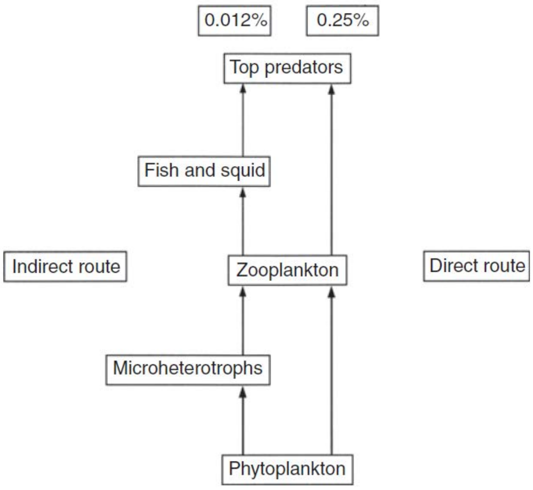


Block diagram from Hempel (1985), modified after Gordon and Goldberg (1970)

Most of the Antarctic has a low primary production. However, certain areas like the ice-edge and the Antarctic convergence in austral summer have high primary production with high concentrations of phytoplankton serving as food resource for zooplankton and krill and otherwise descending into deeper water layers or to the sea bed (Hempel, 1985). The relatively short food chain from primary production to zooplankton/krill and baleen whales (Fig. 3-4) is probably suspect to large influences by humans, as krill and great whales are of economic interest and are exposed to exploitation since the 18th century (Hempel, 1985). In addition to the overexploitation of marine wildlife by man up until the 1960s, climate change adds a further threat especially for long-living species still recovering from whaling and sealing (Nicol et al. 2000, 2008).

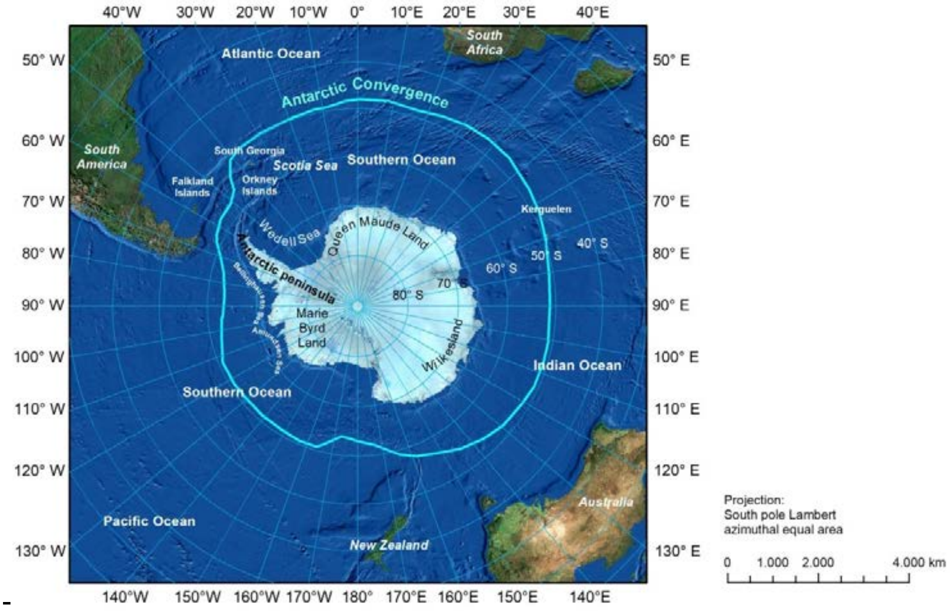
The northern edge of the Antarctic ecosystem is the Antarctic Convergence or southern polar frontal zone – an oceanic frontal system marking the boundary between temperate northern waters and cold southern polar waters (Boyd, 2009a). Within comparably small distances temperature gradients can reach 10°C across the convergence (Boyd, 2009a). Boehme et al. (2008) measured a difference of 6°C south of South Georgia using instruments deployed on elephant seals. Around the Antarctic Convergence also the sub-Antarctic islands are found (Fig. 3-5). The diversity of marine mammals in the Southern Ocean is low, hosting around 20 % of the world's species, but biomass is fairly high probably accounting for 50 % of the marine mammal biomass of the world (Boyd, 2009a).

Fig. 3-4 Diagram showing the energy flow from phytoplankton to marine mammals



From Boyd (2009a): "This diagram shows the more direct route of energy transfer in the Southern Ocean, vs the more indirect route elsewhere. The percentage of the energy taken in by phytoplankton that subsequently reaches the top predators is shown at the top of the diagram."

Fig. 3-5 Antarctica with major sub-Antarctic islands and the approximate location of the Antarctic convergence



3.3 Importance of communication for marine mammals

Communication is a process of conveying information between a sender and a receiver. The successful reception of the sent information alters the probability of a subsequent behaviour in a receiver (Dudzinski et al. 2009) and can facilitate social behaviour. The signal is the vehicle by which information is exchanged and is usually adapted for a balance of optimum transmission in the senders/recipients environment and the need to prevent eavesdropping of conspecifics, predators and prey. Given the highly complex social behaviour found in many marine mammals, communicative behaviour is essential to regulating social interactions for these species. Both the sender and the receiver rely on signals for reproduction, predator defence, territory defence, foraging, maintenance of social bonds and parental care. To understand the importance of communication in a given species in Antarctica, it is therefore important to view the function of the signals (e.g., aggression/submission, mate attraction, parental care, territorial defence, foraging), and whether signals are multi-modal (Dudzinski et al. 2009), hence using multiple methods of communication quasi-simultaneously. This is of lesser importance to this study as it will focus solely on acoustic communication.

Marine mammals evolved in the marine environment where light attenuates rapidly, but sound propagates well. Because of the ease with which sound travels in water and the large area over which sound can be transmitted, underwater acoustic signals evolved to be the principal mode of information transmission for fully aquatic mammals (cetaceans) and a predominant mode for amphibious marine mammals (pinnipeds) especially for long-range communication. Determining the context and function of sounds is difficult. A summary of studies using playback techniques to examine the function of sounds in marine mammals is given by Deecke (2006). The impact that anthropogenic underwater noise may have on the communicative signals of marine mammals has been highlighted in studies of odontocetes (Foote et al. 2004), mysticetes (Croll et al. 2002), and pinnipeds (Southall et al. 2000). The acoustic properties of the communication signals can vary widely – from short pulses to stereotyped whistles to complex songs. However, in order to be useful for communication a signal must also be complex enough to allow encoding the information. Even though the amount of information encoded in communication signals of marine mammals is largely unknown (with possible exception of some stereotyped signature whistles, distress calls of porpoises and probably agonistic sounds of dolphins) it can be assumed that the information content is context specific and will vary with the behavioural state of the sender.

Communication in a noisy environment or over long distances may require the animal to change its signalling strategy. It can increase the complexity of its signals to achieve sufficient redundancy in transmission of the information to the receiver (increase of redundancy within a signal) or it could slow down the information rate and transmit very simple signals over long periods of time to reduce the required bandwidth of the communication channel (increase of redundancy by repetition; Zimmer (2011)).

Generally, sounds of baleen whales are very different from those of odontocetes, with a wide range of types and quantity of signal types across mysticete species. Even though a specific sound has only rarely been associated with a given behavioural event it is proposed that mysticete sounds serve social functions including long-range contact, assembly calls, sexual advertisement, greeting, spacing, threat, individual identification (Dudzinski et al. 2009) and may serve coordination during cooperative foraging events. It is probable that sounds produced by mysticetes serve to synchronize biological or behavioural activities in listeners that promote subsequent feeding or breeding. Generally it is assumed that baleen whales communicate over large distances resulting in a large active communication space. *Active space* is the range or distance (radius) over which a communication signal attenuated by propagation effects remains above the detection threshold of a potential receiver (Brenowitz, 1982). This can be interpreted in the original sense of a linear measure of maximum communication distance like proposed by Marten & Marler (1977).

Odontocetes emit a variety of sounds for communication in forms of whistles (Ford 1989), pulsed calls (Payne and Webb 1971; Ford 1989), and also use the repetitive pattern of clicks to transport information as for example in the form of codas of sperm whales (Watkins and Schevill 1977). Whistles are generally of comparatively lower frequency and are less directional than echolocation signals (clicks), hence providing means for communication over a longer range and generating relatively large active spaces (Janik 2000; Miller 2006). Echolocation clicks, however, are directional signals, of high frequency (Au 1993). Due to the higher absorption rate at high frequencies typical odontocete signals provide smaller communication range and space compared to baleen whales and may hence allow for a direct and private communication between sender and receiver.

The sounds emitted by odontocetes can be divided broadly into two signal types:

a) Pulsed sounds are mainly used for echolocation, i.e. to use the echoes from an emitted animal sound to estimate the location, range and direction of an object (Zimmer 2011). These echolocation clicks can have a broad bandwidth as e.g. in the killer whale (*Orcinus orca*), or are of narrow-band composition as in the harbour porpoise (*Phocoena phocoena*) while beaked whales use frequency modulated sweeps. Odontocetes use echolocation for foraging, orientation and obstacle and/or predator avoidance (Au 1993; Tyack and Clark 2000; Morisaka and Connor 2007). Echolocation signals are usually highly directional and the echoes returning from ensonified objects provide information on the distance to the object as well as information on the angle (both in azimuth and elevation) at which it is positioned and to some degree on the surface structure and material of the object. Echolocation signals are short pulsed signals which are emitted at varying repetition rates. When searching or trying to orient over larger ranges animals emit clicks at a slow succession rate while rates of >1.000 clicks per second can be generated when investigating an object at close range. The high-repetition, burst-pulsed sounds can also have social functions. In non-whistling species as the harbour porpoise they are the only proven type of active communication signal (Clausen et al. 2010). Sperm whales, which also only produce clicks, are an exception in this context as they have dedicated click types with different source properties for echolocation and communication (Madsen et al. 2002 a, b).

b) Narrow-band tonal sounds are continuous signals called whistles (Caldwell and Caldwell 1965, 1990; Tyack 1986; Sayigh et al. 1990). These signals can be highly stereotypic and serve for identification of individual animals, but most whistles serve other but mostly unknown functions.

The sounds produced by pinnipeds are typically frequency modulated or pulsed sounds. Except for male walruses, pinnipeds do not whistle (Dudzinski et al. 2009). Pinniped vocalisation is strongly correlated with mating and the medium (under water or on land). While phocid seals tend to be more vocal under water (especially the true seals that mate in water) otariid seals are much more vocal on land. Polar pinnipeds in general are much more vocal under water than temperate or tropical pinnipeds. Antarctic species, in particular, are vocal when they haul out. Comparing the vocal repertoire of Antarctic phocid seals, Stirling and Thomas (2003) found distinctive differences. Echolocation has not been proven for any pinniped species, even though click-like signals were recorded.

3.4 Masking in the context of scientific evaluation of anthropogenic noise in general

This section is a basis for further scientific discourse regarding masking modelling (as discussed in chapter 7). An accepted idea of marine mammal reactions to noise, however incomplete, are the zones of noise influence presented by Richardson et al. (1995). Within this theoretical framework four zones were defined:

1. Zone of audibility
    - Depending on the hearing ability of the animal
    - Most extensive zone

  - Strictly not a zone of impact, as audibility in itself does not constitute impact. Can, however, serve as an extremely precautious upper limit on range of influence.

2. Zone of responsiveness
    - The sound causes a behavioural or physiological reaction of the animal
    - Smaller than the zone of audibility.
3. Zone of masking
    - A noise signal interferes with perception of other sounds of importance to the animal: e.g. communication, echolocation, prey sounds, predator sounds or other sounds important for auditory scene analysis.
    - Size of the zone is highly variable and depends on both masking sound and masked sound.
4. Zone of hearing loss, discomfort or injury
    - Most likely the smallest zone, very close to the sound source.

Estimating the size of the different zones presents a challenging task, even for those which are better defined. The fourth zone for instance is frequently used associated with a temporary or permanent threshold shift (TTS/PTS) as presented by Southall et al. (2007) who developed exposure criteria based on US regulations. Nevertheless PTS has never been measured deliberately (in a designed experiment) in any marine mammal, while a temporary threshold shift (TTS) has actually been measured on some species of pinnipeds and odontocetes (Finneran et al. 2010, Kastak and Schusterman 1996; Kastak et al. 2005; Lucke et al. 2009; Popov et al. 2011 a,b; Schlundt et al. 2000). For the zone of masking the uncertainties surrounding estimation is much higher and the extent is likely to vary across the entire range from almost equal to the zone of audibility (for very loud constant noise close to the animal, overlapping in frequency content) to below the zone of hearing loss, discomfort and injury (for impulsive noise, no overlap in frequency spectrum etc.). The size of this zone strongly depends on the masking noise and the signal being masked. Several experiments were conducted to measure the zone of responsiveness for marine mammals (e.g. Brandt et al. 2011; Frankel and Clark 2000; Madsen et al. 2006; Mccauley et al. 1998; Tougaard et al. 2009) in the wild. However, studies on masking have to evaluate the absence of a possible behavioural reaction to a signal. One approach to estimate these effects for killer whales and vessel noise experimentally was presented by Bain and Dahlheim (1994) and another by Erbe et al. (2008) for beluga whales. For most other marine mammal species such trials in captivity are either not possible (Baleen whales, sperm whale, beaked whales) or have not been performed yet. Hence evaluation has to consider the hearing abilities of the species and take source levels, similarity in frequency content and loudness of the transmitted signal and the spectral content of the noise into account. Relationships differ, when either the sender is masked by a nearby sound source, or the receiver is masked. For seismic airgun pulses it is probable, that a masking potential exists due to signal stretching during transmission over large distances (Gedamke and McCauley 2010). Behavioral changes were documented for instance for blue whales which were tagged and exposed to controlled stimuli (Goldbogen et al. 2013). Such controlled exposure experiments could be used to estimate masking influences as well.

One important point is the definition of masking, as it affects how calculations were carried out. The definition within this project is as follows: MASKING: is a noise-induced elevation of detection thresholds. In effect, this reduces the signal to noise ratio (SNR) available to the animal. Such *Neuronal masking* (masking *sensu strictu*) occurs, whenever somewhere in the auditory pathway the same neurons have to transmit both the signal as well as masking noise at the same time. Masking is then instantaneous and occurs only, when signal and noise have a sufficient overlap in time and frequency content and the masker is (roughly) at least as loud as the signal. Because marine mammals, as all other vertebrates have two ears, it is often also required that the bearing to the noise source and the signal is roughly the same for maximal masking to occur.

Other effects than neuronal masking can be included in a definition of *masking in general* (*sensu latissimo*). These are the stapedius reflex, neural accommodation and attention effects and even TTS. The *stapedius reflex* protects the animal from hearing damage by a loud source of any frequency, for instance from the animals own vocalisations by reducing the capabilities to physically transmit oscillations in the inner ear. This occurs by a rapid contraction of the stapedius muscle, which increases the stiffness of the middle ear. A stapedial reflex occurs either shortly [ms] after onset of impulsive sound or if the animal is expecting the sound (e.g. for a rhythmic sound) and has recently been demonstrated in grey seals (Götz et al. 2011). There is a delay of the effect to wear of, but it is only on the order of tens of milliseconds. *Neuronal accommodation* is similar to the stapedius reflex but it occurs in the nervous system and is due to the refractory time of auditory neurons following a large stimulation. This also takes place at a time scale of few milliseconds. *Attention* of animals may reduce over time, when a loud sound source is present for a longer time and the animal either turns its attention away from the masking sound or starts to direct its attention towards the masking sound altering the threshold to receive other signals thus increasing a possible masking effect. *Auditory fatigue* in terms of *TTS* can lead to a prolonged time of elevated thresholds on the order of hours or even days after intense noise exposure (Lucke et al. 2009). There are indices, that TTS is not fully reversible (Kujawa & Liberman 2009; Lin et al. 2011) and directly damages cells. This means that TTS is a form of masking and injury. The effect can be large, but is not the focus of this research, as it must be accounted for, when assessing the zone of hearing loss, discomfort and injury.

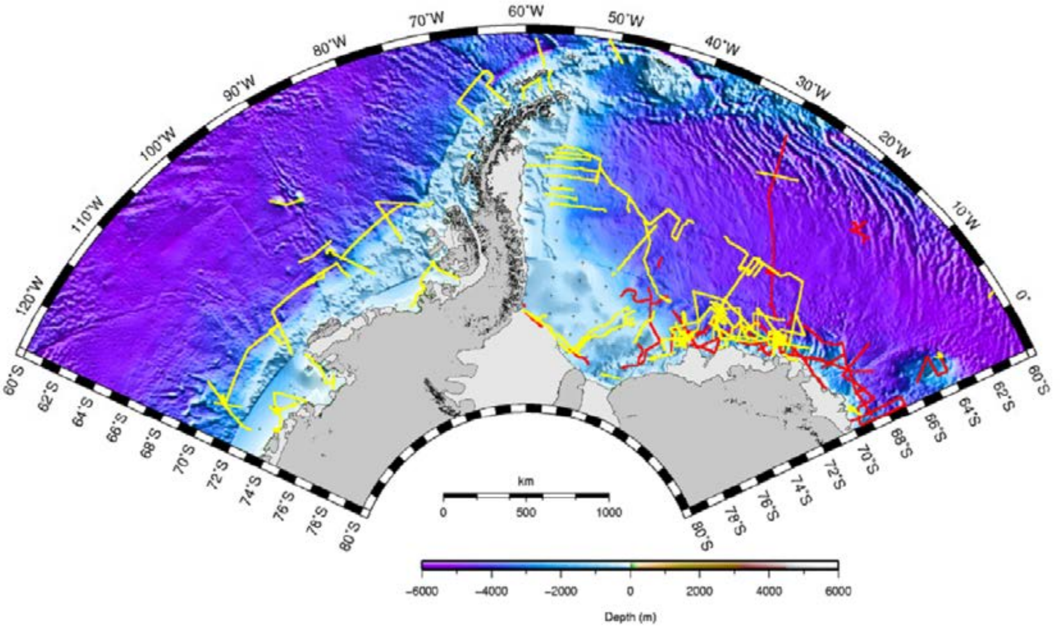
Masking within this report will be discussed as *Neuronal masking* (masking *sensu strictu*) with the exception that we cannot account at the moment for a difference in bearing towards the masker. Marine mammals can estimate a bearing towards a sound signal. With increasing angle between two sound sources it becomes easier to differentiate those sources. Currently, there are no data available to make predictions on directional hearing of baleen whales, In the same fashion the models used cannot account for any change in the sender, as for instance a change in call rate or adapted source level would result in a higher detection probability by the receiver. However if sound assumptions can be developed for the species considered, it would be easy to implement in a second step of the modelling approach.

Masking is effectively reducing the active space of marine mammals – this can be due to increased background noise level, other natural sound sources like sediment noise in shallow areas and of course anthropogenic sound sources like ship noise or potentially seismic airguns. If animals are able to perceive sound below natural background noise levels at sea, then their active communication space is limited by background noise levels and may vary even under natural circumstances. This modelling exercise will study the potentially far reaching masking effects of seismic airguns on Antarctic marine mammals.

3.5 Use of airguns for German scientific purposes in the Antarctic Treaty area

Surveys using high pressured airgun shots for seismic exploration were carried out in the AT area by the research vessel R/V Polarstern for 22 years from 1985/86 until 2007 (Boebel et al. 2009). 14 cruises south of 60°S with an average of 310 hours of operation, releasing on average 74,476 shots per cruise on 1829 km mean transect length per cruise (Boebel et al. 2009). The main target areas during these cruises were the Amundsen, Bellingshausen and Weddell Sea (Fig. 3-6).

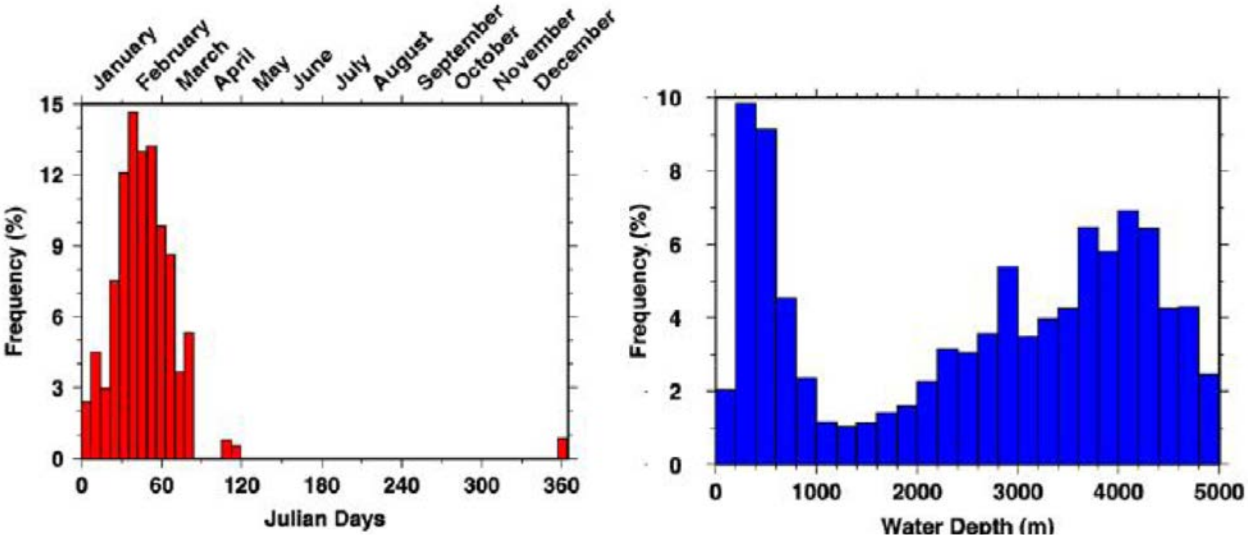
Fig. 3-6 Seismic tracks oft the R/V Polarstern from 1985 to 2007



Surveys were carried out by the Alfred Wegener Institute for Polar and Marine Research (yellow lines) and the German Federal Institute for Geosciences and Natural Resources (red lines). From Boebel et al. (2009).

The following information are an extract from Boebel et al. (2009). Surveys were mostly carried out in water depth of more than 4,000 m. The longest cruise was in the austral summer 1996/97 with 4,415 km profile length, approximately 477 h of operation and 114,414 shots. The estimated number of total shots for the Amundsen/Bellingshausen Seas was 189,593 shots based on a shot interval of 15 s and a cruise speed of 15 kn (knots). For the Weddell Sea 656,735 shots were calculated. Seismic operations were carried out during the austral summer when ice floes do not pose a major risk for the scientific equipment. In the Weddell Sea surveys were conducted from late December to late March and in the Bellingshausen and Amundsen Sea operations lasted from January to late April. Nearly all survey activity was clustered between Julian days 0-90 (Fig. 3-7, left). With regard to water depth the seimic operations showed a clear preference for the two clusters between 200 and 600 m and 2,200 to 4,800 m (Fig. 3-7, right).

Fig. 3-7 Left: Seasonal usage of airguns in Antarctica by R/V Polarstern in the Bellingshausen/Amundsen and Weddell Sea; Right: water depth distribution during seismic surveys of R/V Polarstern; both from Boebel et al. (2009)



Airguns produce impulsive signals that are propagated over vast distances, even though only the proportion of sound directed at the sea floor is used within the scientific experiments and geophysical exploration. Airguns mostly produce low frequency sounds that correspond to the frequency range some Antarctic baleen whales predominantly use for communication. Airguns have been considered for potentially deleterious effects in close distances (e.g. Gordon et al. 1998; Yazvenko et al. 2007; Erbe and King 2009; Breitzke and Bohlen 2010). Masking, as a far reaching effect, however was only partly considered within research studies and impact assessments: Only few studies have considered the potentially adverse effect that masking through airguns can have on marine mammals in large distances.

Airgun sounds sounds can also be perceived above ambient sound levels over large distances in water and sound waves are reflected multiple times on the water surface and diffracted in sound channels (Urick 1983). The frequency content of the received signal at distance, as well as the length of the received wave form, changes due to signal stretching which may cover the whole period between successive airgun shots. Hence, the impulsive sound that airguns emit can develop continuous properties through sound propagation effects and may lead to a general increase in background noise level. Furthermore if received levels are above the hearing thresholds of marine mammals, stretched airgun signals may lead to continuous masking effects.

Within this study we are interested in the distance, where sound develops continuous properties and the potential masking effects of both *continuous* and *intermittent* (not continuous) received sounds of airguns.

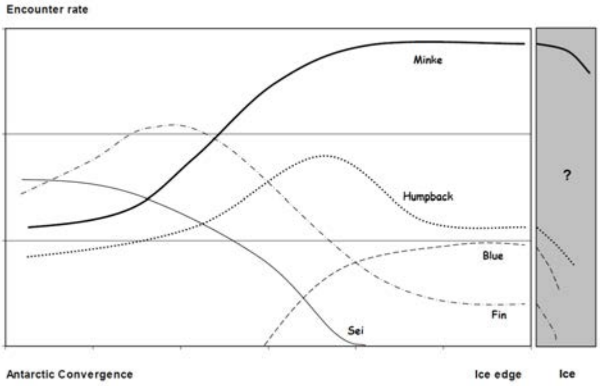
4 Species of Concern

The literature review compiles knowledge on Antarctic species based on three key documents. Those are the six volumes of the Handbook of Marine Mammals (ed. Ridgway & Harrison), the Encyclopedia of marine mammals (ed. Perrin, Würsig & Jefferson), the literature review by Gill and Evans (2002). More recent information is taken into account especially for vocalisations, abundance and distribution data. For these species descriptions the mysticetes (baleen whales), the odontocetes (toothed whales) and the pinnipeds (seals) are considered.

4.1 Baleen Whales (Mysticetes)

Within this review we have considered blue whales (*Balaenoptera musculus*), fin whales (*B. physalus*), sei whale (*B. borealis*), Antarctic minke whales (*B. bonarensis*) and humpback whales (*Megaptera novaengliae*) from the family Balaenopteridae and southern right whales (*Eubalaena australis*) from the family Balaenidae. Mainly sub-Antarctic species like common or dwarf minke whales (*B. acutorostrata*) and pygmy right whales (*Caperea marginata*) are only considered where appropriate within the more dominant species profile, as there is very little knowledge about them (Leaper et al. 2008a) and an overlap with seismic activities of the 'Polarstern' is most probably small. All of these species have a circum-global distribution and occur in the waters south of 60° southern latitude. They do show large differences in relation to the position of the ice edge with minke whales showing a preference for the ice edge, while fin and especially sei whales clearly avoid this region (Fig. 4-1).

Fig. 4-1 Occurence of mysticetes in the Antarctic region with regard to the ice edge

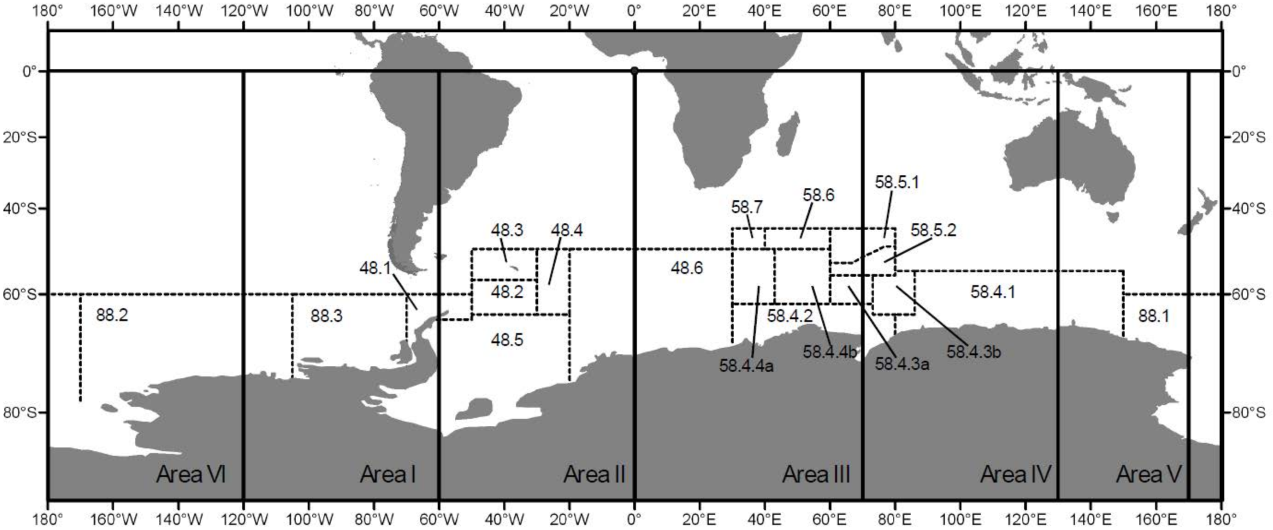


Reproduced from Leaper et al. (2008a), adapted from Kasamatsu et al. (1996)

The two latest papers published on this topic presented occurrence and abundance data from the Antarctic region, summarizing mainly surveys and catch data collected for the IWC and CCAMLR) by Kasamatsu et al. (1996) and Leaper et al. (2008a). To describe geographical distribution, the area was divided into management or statistical areas (Leaper et al. 2008a). Data from the International Decade for Cetacean Research (IDCR), Southern Ocean Whale and Ecosystem Research (SOWER), CCAMLR 2000 Survey, Southern Ocean Global Ocean Ecosystems Dynamics (SO-GLOBEC), research programs on national scale and Japanese Whale Research Program Under Special Permit in the Antarctic (JARPA) were compiled (Fig. 4-2).

Mysticetes were heavily hunted until the 1960s in the southern hemisphere (Boyd 2009a; Gambell 1993; Leaper et al. 2008a). Recovery can be documented for some species like southern right whales (Best 1993), but is still very uncertain for others.

Fig. 4-2 Management or statistical areas of the IWC



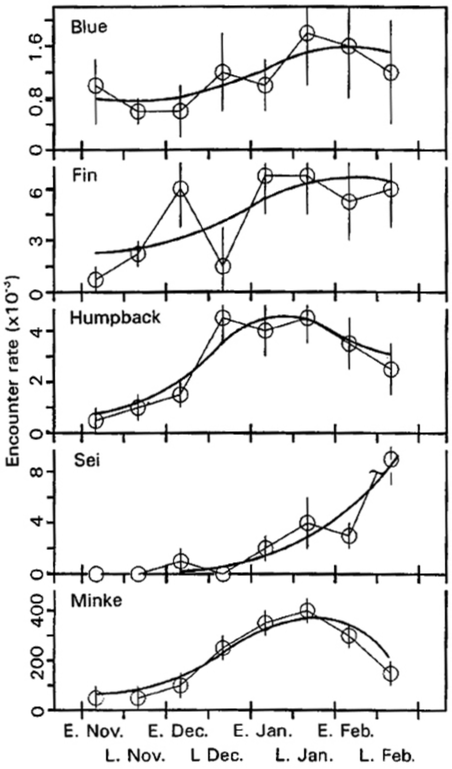
Management or statistical areas of the IWC within Antarctica (solid lines) and CCAMLR (dotted lines), reproduced from Leaper et al. (2008a). For this study, Area I and II as well as 88.2 (including the Amundsen Sea), 88.3 (Bellingshausen Sea), 48.1 (intermediate between Bellingshausen und Weddell Sea) and 48.5 (Weddell Sea) are most important.

As surveys are scarcely conducted and there is no adequate knowledge of distribution for some species, we take ecology models described in Kaschner et al. (2006) updated with newer data into account. These models predict the probability of habitat suitability based on environmental conditions known (temperatures, depth, distance to land and others). Maps and data of habitat suitability are available at http://www.sealifebase.org/.

Different Baleen whales show variable encounter rates in visual surveys, with maximum occurrence between mid-December to mid-February (Fig. 4-3; Kasamatsu et al. 1996)

Fig. 4-3 Seasonal occurrence of Antarctic Mysticetes

Open circles with vertical lines show the encounter rates by half-month and their standard errors. Solid lines show the running mean of the half month encounter rates (taken from Kasamatsu et al. 1996).

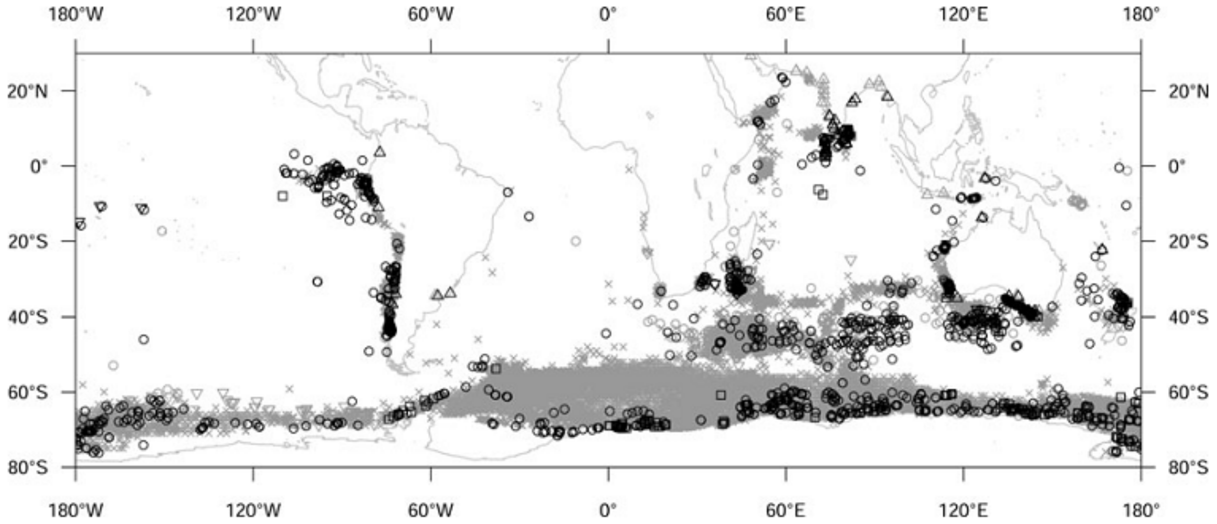


4.1.1 Blue Whale

Order	Cetacea
Suborder	Mysticeti
Family	Balaenopteridae
Species	*Balaenoptera musculus* (Linnaeus, 1758)
Subspecies	Antarctic blue whale *B. m. intermedia* Pygmy blue whale *B. m. brevicauda* Blue whale *B. m. musculus* (northern hemisphere)

Blue whales are found worldwide (Sears and Perrin 2009) and their migration patterns seem to be highly diverse (Reilly et al. 2008a). Of the three designated subspecies *B. m. intermedia* is the largest in size. Differences between *B. m. intermedia* and *B. m. brevicauda* were found in available catch information suggesting that pygmy blue whales are seen in lower latitude and may be geographically segregated in mid austral summer from Antarctic blue whales, being found in more northerly waters at that time (Kato et al. 1995). Subspecies designation is generally accepted even though scientific evidence needs to be stronger (Sears and Perrin 2009). Branch et al. (2007, 2009) and Sremba et al. (2012) provided these evidences based on analysis of old whaling data and genetic research. Pygmy blue whales records are found in less than 1 % of the sightings from south of 52° S (Branch et al. 2007; Branch 2006a), hence their evaluation within this project is not a primary task. Nevertheless, historic catches indicate, that pygmy blue whales were caught quite frequently south of 60°S (discussed in Gill and Evans 2002).

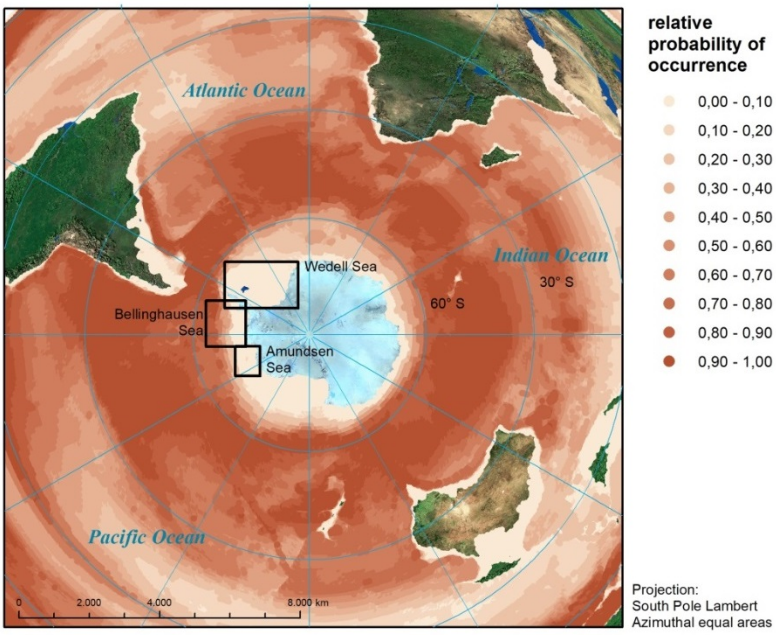
Fig. 4-4 Distribution of blue whales



Distribution of blue whales in all months based on catches (x), sightings (O), strandings (Δ), acoustic records (❑) and Discovery mark positions (▽). Grey is used for positions ≤1973 and black for >1973 (Branch et al. 2007).

Antarctic or true blue whales' natural abundance before whaling was estimated to be 239,000 individuals (202,000-311,000) which decreased to lows of 360 individuals (150-840) in 1973 (Branch et al. 2004). Branch et al. (2004) also showed that the population has most probably increased from 1968 to 2001 with a rate of 7.3 % per year. This complies with findings from Matsuoka et al. (2006). With the most recent abundance estimate of 2,249 individuals (95 % CI 1,140-4,000; Branch 2007a) Antarctic blue whales are now within 1 % of their original population size prior to whaling. *B. m. intermedia* undertakes long migrations not only between their austral summer feeding grounds close to Antarctica (October to April) and their austral winter breeding grounds in southern Africa, eastern tropical Pacific, northern Indian Ocean, southwest Australia and north off New Zealand, but also undertakes long longitudinal movements (Branch, 2007a; Leaper et al. 2008a). Breeding grounds are thought to be north of 50°S as discussed by Gill and Evans (2002) and Yochem and Leatherwood (1985). On the western Antarctic Peninsula continuing calls during winter indicate a year-round presence of Antarctic blue whales (Širović et al. 2004, 2009). Highest encounter rates were documented between 66 and 70°S (Kasamatsu et al. 1996).

Fig. 4-5 Native distribution map of blue whales in the Southern Ocean[6], only areas in brown to white shades are modelled outcome, blue areas are not included in the model.



During whaling, most catches occurred within the Antarctic Polar Front, but more recently Antarctic blue whales are closer associated with pack ice (Leaper et al. 2008a). This could be due to more survey effort in lower latitudes than 60°S in recent years (Leaper et al. 2008a), but also to an association with higher krill abundance (Branch et al. 2007). Blue Whales prey on krill, mostly *Euphausia superba*, and other crustacean meso-zooplankton (Branch et al. 2007). Murase et al. (2002) reported visual sightings of blue whales in close vicinity to the ice edge associated with high krill abundance. The only predators of blue whales are most probably killer whales (Sears and Perrin 2009), but only few incidents were reported (Tarpy 1979 in Yochem and Leatherwood 1985; Pitman et al. 2007b; reviewed in Ford and Reeves 2008).

Blue whales travel alone or in pairs, but in areas of high productivity there can be groups of 50 animals or more (Sears and Perrin 2009). Blue whales are listed in the IUCN Red List as “Endangered A1 (abd)” (Reilly et al. 2008a). Population structure remains unclear, but indices based on regional differences in song have been developed showing great stability over more than 30 years (McDonald et al. 2006b). The habitat suitability model (Fig. 4-5) shows a circumpolar distribution with high suitability in the Bellingshausen Sea and low suitability in the Weddell and Amundsen Sea, showing a good match with observed data (Fig. 4-4) from Branch et al. (2007).

Blue whales use different song types. Songs are used by different groups and the vocalisation can vary seasonally. For singing they use stereotypic sound types in regular succession. In contrast, they use individual, transient sounds for calling at irregular intervals. Their song also seems to

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[6] Computer Generated Native Distribution Map of Balaenoptera musculus (reviewed). www.aquamaps.org, version of Aug. 2010. Web. Accessed 27 Aug. 2012. Expert remarks: Good correlation with known species´ occurrence. Modification of temperature and salinity range to capture this species´ distribution. Predicted presence in the Red Sea, Sea of Okhotsk, Sea of Japan, northern Bering Sea and Beaufort Sea is not supported by published data. Predictions are a compromise between summer and winter distribution and potentially there is a difference in habitat uasge in different oceans (less close to ice edge in the northern hemisphere?). Predictions would be improved by use of seasonal predictions. Kristin Kaschner, 2009-11-21

be subject to change over time (Gavrilov et al. 2011, 2012). (McDonald et al. 2006b). Blue whales (mostly *B. m. musculus*, but also *brevicauda*) have been reported to react towards low frequency sound like active signals (Aburto et al. 1997), mid-frequency sonar (Melcón et al. 2012; Goldbogen et al. 2013) and seismic surveys (Di Iorio and Clark, 2009). For Antarctic blue whales maximum detection ranges have been estimated between 200 km and 80 km (Samaran et al. 2010b). For pygmy blue whales this distance was found to be 300 km, but most calls came from about 70 km (Samaran et al. 2010). These results are in line with findings from Širović et al. (2007) for Antarctic blue whales (200 km range) and Stafford et al. (1998) for northern blue whales.

Table 4-1 Parameters of vocalisations of blue whales

Signal type	Frequency range (Hz)	Frequency near Maximum Energy (Hz)	Dominant frequencies (Hz)	Source level (dB re 1 µPa at 1 m)	References
moans	12-390		16-25		Cummings and Thompson, (1971, 1994); Edds (1982); Stafford et al. (1994) Wartzok and Ketten, (1999)
	12-400	12-25		188	
clicks	6,000-8,000 21,000-31,000		6,000-8,000 25.000	130,159	Beamish and Mitchell (1971); Beamish (1979)
downswept tones (calls)	16-100		80-30	188	McDonald et al. (2006b)
calls (multiple parts) A part (AM) B part (downsweep) C part (FM) D part (up-sweep)	9-90 28 28-19 19-16 60-45	20,25,31.5			Cummings and Thompson, (1971) McDonald et al. (2001) Mellinger and Clark, (2003) McDonald (2006b)
arch sound	70-35				Mellinger and Clark, (2003)
Southern Ocean blue whale song	16-28			189	Širović et al. (2004) Stafford et al. (2004) McDonald et al. (2006b) Širović et al. (2007)

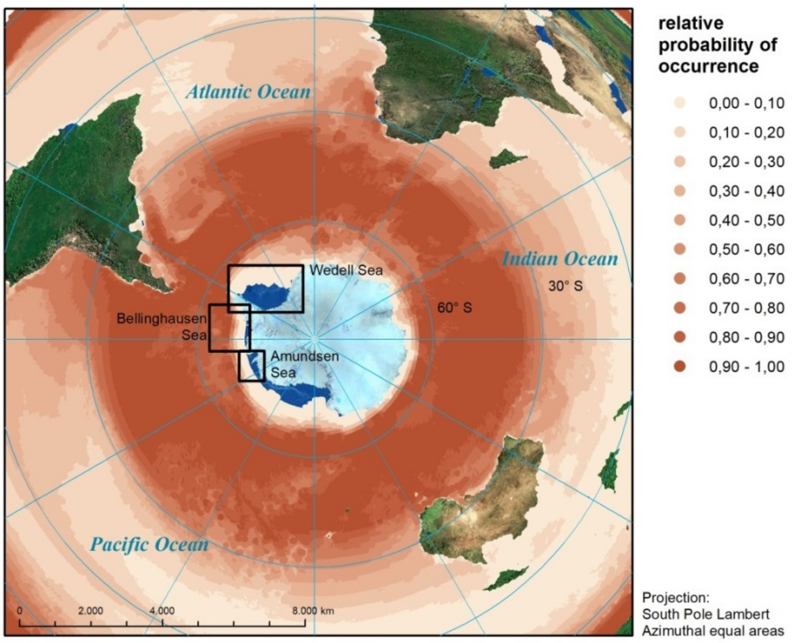
4.1.2 Fin Whale

Order	Cetacea
Suborder	Mysticeti

Family Balaenopteridae

Species *Balaenoptera physalus*

Fig. 4-6 Native distribution map of fin whales in the Southern Ocean[7], only areas in brown to white shades are modelled outcome, blue areas are not included in the model.



Two forms of fin whales can be separated, *Balaenoptera physalus physalus* in the northern Hemisphere and *Balaenoptera physalus quoyi* in the southern hemisphere (Aguilar 2009). This separation is probably caused by genetic isolation of the northern and southern hemisphere animals with alternating seasonal migration patterns. *B. P. qouyi* shows a circumpolar distribution in farther distance to the ice-edge than blue and minke whales. Habitat suitability (Fig. 4-6) for this species seems to be high for the Bellingshausen Sea, but not for the Weddell and Amundsen Sea.

During austral summer, occurrence of fin whales decreases south of the Antarctic convergence towards the ice-edge. In the southern Pacific distribution peaks between 58°S and 62°S and in the Atlantic it shifts northerly, with the exception of the tip of the Antarctic Peninsula (Gill and Evans 2002; Kasamatsu et al. 1996). In winters they may migrate towards southern Africa (Reilly et al. 2008b). Fin whales are feeding in the summer and breeding and fasting during the winter months (Aguilar, 2009). According to Laws (1961) cited in Gill and Evans (2002) pregnant females initiate the migrations and adult males and resting females and lastly immature animals follow. They seem to stay longer in the Antarctic than blue and sei whales and older animals may travel further south (Gambell 1985a).

Fin whales are probably guided during their migration by the geomagnetic field (Walker et al. 1992). Fin whales travel alone or in small groups of usually up to two, more uncommonly up to

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[7] Computer Generated Native Distribution Map of Balaenoptera physalus (reviewed). www.aquamaps.org, version of Aug. 2010. Web. Accessed 14 Aug. 2012. Expert (see below) remarks: Good fit with known species´ distribution. Minor modification of salinity and temperature ranges to capture this species´ maximum range extents. Predicted occurrence constitutes a compromise between summer and winter distribution. This species´ preferred temperature ranges are from polar to warm temperate waters, occurrence in tropical waters is rare. Probably false predicted absence from the Baltic Sea and false predicted presence in Hudson´s Bay. Kristin Kaschner, 2009-09-10.

seven animals. However, in areas of high productivity they can form large aggregations. At the feeding grounds fin whales schools are often mixed with blue whales. Sometimes this results in interspecific competitions and hybrids. There is a strong social bond between cows and their calfs (Aguilar, 2009). The only predators of fin whales are killer whales (*Orcinus orca*). Fin whales often show teeth marks but are able to survive these attacks, most probably due to their ability to reach and maintain high swimming speed (Aguilar 2009). Essentially fin whales in the southern hemisphere feed on krill, *Euphausia vallentini.* However, the diet varies with season and area and they also prey on other planktonic crustaceans (Aguilar 2009).

Pre-whaling estimates of abundance are very uncertain, but Gambell (1985a) reports 490.000 animals at the beginning of the 20th century for the southern hemisphere as probable. World-wide it is estimated at 84.000 and south of 60°S recent estimates range from 4,300 (CV=0,46) to 8,800 (CV=0,56) depending on assumptions of the data interpretation (Branch and Butterworth 2001 and Leaper et al. 2008a). Fin whales are listed in the IUCN Red List as “Endangered A1 (abd)” (Reilly et al. 2008b). Fin whales are vocally active and use their relatively simple sounds for social interactions (Aguilar 2009; Clark 2002; Croll et al. 2002; Simon et al. 2010). One specific feature of their vocalisation are 20 Hz pulsed sounds (Thompson et al. 1992; Watkins et al. 1987). Castellote et al. (2010, 2012) have shown that fin whales alter their vocal behaviour by shortening and decreasing the bandwidth of 20 Hz song notes during exposure to ship noise and airgun signals in concurrence with a probable longer lasting displacement. Sounds of fin whales were recorded during seismic surveys for a long duration of over a year by Nieukirk et al. (2012) implying that animals were exposed to very loud sounds for a long time.

Table 4-2 Parameters of vocalisations of fin whales

Signal type	**Frequency range (Hz)**	**Frequency near Maximum Energy (Hz)**	**Dominant frequencies (Hz)**	**Source level (dB re 1 µPa at 1 m)**	**References**
moans, downsweeps	14-118	20	20	160-186	Watkins (1981a); Watkins et al. (1987); Edds (1988); Cummings and Thompson (1994)
moans	16-750	20		160-190[e]	Wartzok and Ketten, (1999)
constant call	20-40				Edds (1988)
moans, tones, upsweeps	30-750			155-165	Watkins (1981b); Cummings et al. (1986); Edds (1988)
rumble	10-30	<30			Watkins (1981b); Edds (1988)
whistles?, chirps?	1,500-5,000		1,500-2,500		Thompson et al. (1979)
clicks?	16,000-28,000				Thompson et al. (1979)
pulse	40-75 90				Wartzok and Ketten, (1999)

Signal type	Frequency range (Hz)	Frequency near Maximum Energy (Hz)	Dominant frequencies (Hz)	Source level (dB re 1 µPa at 1 m)	References
	18-25 28-15	20		189	Širović et al. (2004); Širović et al. (2007)
ragged pulse	<30				Wartzok and Ketten, (1999)

? Denotes infrequently recorded and/or questionable correlation of sound with species

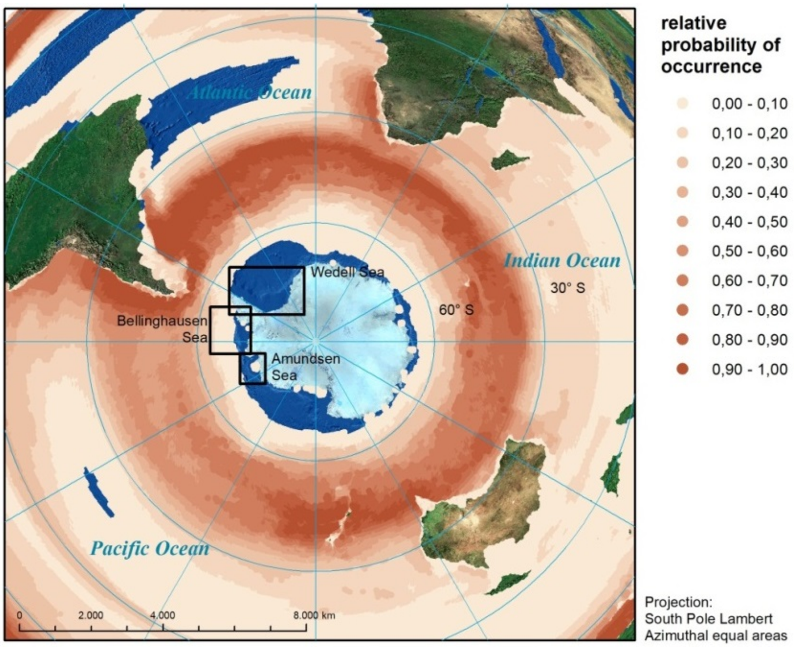
4.1.3 Sei Whale

Order	Cetacea
Suborder	Mysticeti
Family	Balaenopteridae
Species	*Balaenoptera borealis*

Sei whales are common in all ocean basins, less so in areas closer to coasts (Horwood 2009). They spend the austral summer in Antarctica and migrate back to their calving grounds in winter. Their arrival time in Antarctica is later than for the other baleen whales showing elevated occurrence starting in January (Kasamatsu et al. 1996). They do not migrate as far south as blue or minke whales but stay mainly north and around the Antarctic convergence (Horwood 2009). Unlike the other baleen whales that undertake long migrations between feeding and calving habitats, a clear genetic or morphometric difference between northern and southern hemisphere sei whale was not found yet (Kanda et al. 2006).

As for all large whales, sei whales were seriously depleted during whaling times from originally thought 100.000 specimens in the southern hemisphere (Horwood 2009) or even 150,000 to 225,000 (Leaper et al. 2008a). Estimates of data from Japanese catch and scouting vessels show a decline from 64,000 (1960) to 11,000 (1979) animals of legal size for catch excluding the south Atlantic sector (Leaper et al. 2008a).

Fig. 4-7 Native distribution of Sei whales in the Southern Ocean[8], only areas in brown to white shades are modelled outcome, blue areas are not included in the model.



Sei, gray and probably minke whales can feed very close to the water surface in lower prey density areas by skimming the surface with fine fringe fibres on the baleen plates (Gambell 1985b). They feed on copepods and euphausiids (krill), but also on fish shoals and squid (Gambell 1985b; Horwood, 2009). Usually they travel in small groups of around 6 specimens, but larger concentrations of 20-100 individuals can be found on feeding grounds (Gambell 1985b; Horwood 2009).

Sei Whales are listed in the IUCN Red List as “Endangered A1 (abd)” (Reilly et al. 2008c).

Baumgartner and Fratantoni (2008) linked vocal activity of sei whales to a vertical migration of one major prey item *Calanus finmarchicus* (copepods). Sei whales showed more vocal activity during daytime when *C. finmarchus* may be more difficult to catch at further away from the surfacwe for the surface feeding adapted sei whales. Low frequency downsweep vocalisations below 100 Hz were attributed to sei whales in the northern Atlantic (Baumgartner et al. 2008). In Antarctic waters sei whales also produced swept calls (McDonald et al. 2005). About half of the recorded tonal frequency sweeps consisted of multiple parts with a frequency step. During an experiment in the North Atlantic sei whales produced high amplitude calls usable for long distance passive acoustic localization (Newhall et al. 2012). Whales produced signals mostly in pairs in mid water depth probably using the longer reception ranges provided by the sound channel.

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[8] Computer Generated Native Distribution Map of Balaenoptera borealis (reviewed). www.aquamaps.org, version of Aug. 2010. Web. Accessed 14 Aug. 2012. Expert remarks: Modified SST envelope to reflect the more temperate occurrence of this baleen whale species. Extended primary production envelope, since species, as a filter feeder, is likely to be directly associated with areas of high primary production. However, species is known to be migratory and predicted distribution represents a compromise between summer and winter occurrence and thus might not capture most northern and southern range extents completely accurate. Kristin Kaschner.

Table 4-3 Parameters of vocalisations of sei whales

Signal type	Frequency range (Hz)	Frequency near Maximum Energy (Hz)	Dominant frequencies (Hz)	Source level (dB re 1 µPa at 1 m)	References
fm sweeps	1,500-3,500	3000			McDonald et al. (2005); Wartzok and Ketten (1999)
broadband calls (growls and whoosh)	100-600				McDonald et al. (2005)
tonal and upsweep calls	200-600			156	McDonald et al. (2005)
downsweeps	100-44 82-34 39-21				Rankin and Barlow (2007); Baumgärtner et al. (2008)

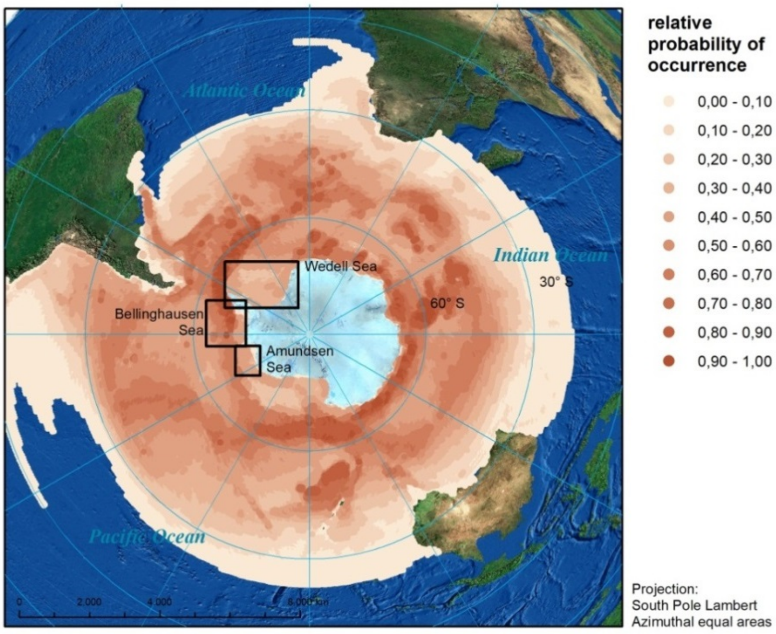
4.1.4 Antarctic Minke Whale

Order	Cetacea
Suborder	Mysticeti
Family	Balaenopteridae
Species	*Balaenoptera bonaerensis*

Currently three forms of minke whales are distinguished worldwide: the Antarctic, common and dwarf minke whale. Genetic evidence led to the recognition of the Antarctic minke whale as a separate species *Balaenoptera bonaerensis* in the 1990's, while the common and dwarf minke whales are both still regarded as *B. acutorostrata,* (Rice 1998).

Antarctic minke whales have a circumpolar distribution in the Southern Ocean with predominantly oceanic feeding grounds and dispersed breeding populations (Kasamatsu and Joyce 1995). They are usually found alone or in small groups of two to three animals. However, sightings of groups consisting of up to 400 animals have been reported from the high latitudes (Perrin and Brownell 2009).

Fig. 4-8 Native distribution map of Antarctic minke whales in the Southern Ocean[9], only areas in brown to white shades are modelled outcome, blue areas are not included in the model.



Antarctic minkes alternate between their breeding grounds 10 - 30°S in austral winter and their feeding grounds in the Southern Ocean in austral summer, where they are mostly found in an area ranging from 60°S to the ice edge (Perrin and Brownell 2009). *B. bonaerensis* is also known to occur beyond the ice edge in the pack ice zone (Scheidat et al. 2011; Gutt et al. 2010; Shirihai, 2008) but the proportion of animals found inside the pack ice is still under debate (Murase et al. 2005; Scheidat et al. 2007; Shimada and Kato 2007; Leaper et al. 2008, Kelly et al. 2010). Ainley et al. (2011) propose that the habitat of the pagophilic Anarctic minke whales might diminish significantly as sea ice cover retreats in a climate change scenario with increasing surface water temperatures, thus leading to a potential increase in intra- and interspecific competition.

Although austral winter sightings of Antarctic minke whales have been reported (e.g. Ribic et al. 1991; Thiele et al. 2004) it remains unclear whether these sighted animals truly overwinter in the pack ice regions (Leaper et al. 2008a).

The IWC estimate applies to the years 1982/83 - 1988/89 giving an approximate point estimate of 760,000 animals (95% confidence limits: 510,000 - 1,140,000[10]) (Reilly et al. 2008e). The older estimates are based on the results of the circumpolar IDCR/SOWER surveys conducted under the

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[9] Computer Generated Native Distribution Map of Balaenoptera bonaerensis (reviewed). www.aquamaps.org, version of Aug. 2010. Web. Accessed 22 Aug. 2012. Expert remarks: Good match with known species occurrence and maximum range extent although the delineation of species distribution is hampered by the difficulties to distinguish it from its sister species, B. acutorostrata, at sea. Modification of upper thresholds of default SST, salinity and sea ice concentration envelopes was necessary to capture all aspects of known range extent. Original predictions for the species based on the RES approach showed strong correlations with observed occurrences (IDCR-SOWER cruises, Kaschner et al, 2006), but AquaMaps predictions, based on a slightly modified algorithm and slightly different environmental input data sets have not been tested yet, although visual comparisons show strong similarities between both sets of predictions. Predictions represent a compromise between summer and winter distributions and would be improved by the incorporation of seasonal aspects.2010-09-04, Kristin Kaschner.

[10] (www.iwcoffice.org, assessed 2012/08/24)

aegis of the IWC from 1978/1979 to 1988/89 (Haw 1993, Leaper et al. 2008a). Three circum-Antarctic sets of surveys have been conducted to date. The estimated number of minke whales declined from the second to the third survey set (1993-2002) to 574,000 (Bravington and Hedley, 2012). Whether these numbers mirror a true decline in population size, a potential shift in habitat use from ice free to ice areas, or result from changes in field methods and statistics is still under debate and research on estimating abundance of minke whales in ice areas is therefor of high priority.

Antarctic minke whales are not classified in a conservation status in the IUCN Red List because they are in the category “data deficient” (Reilly et al. 2008d). Survey results point towards a decline in abundance. If this proves to be real, then Antarctic minke whales would be “Endangered”, if not then they would fall under “Least Concern”.

Antarctic minke whales are thought to feed primarily on krill, but the diet varies with season and area. For example they also prey on copepods and diverse fishes (Perrin and Brownell 2009, Armstrong and Siegfried 2004). A strong correlation between minke whales and killer whale populations was found by Kasamatsu et al. (2000) indicating that minke whales are indeed one major food item for killer whales.

The habitat suitability model (Fig. 4-8) for Antarctic minke whales predicts a circumpolar distribution with high relative probability of species occurrence between approximately 40°S and the Antarctic continent.

4.1.5 Dwarf Minke Whale

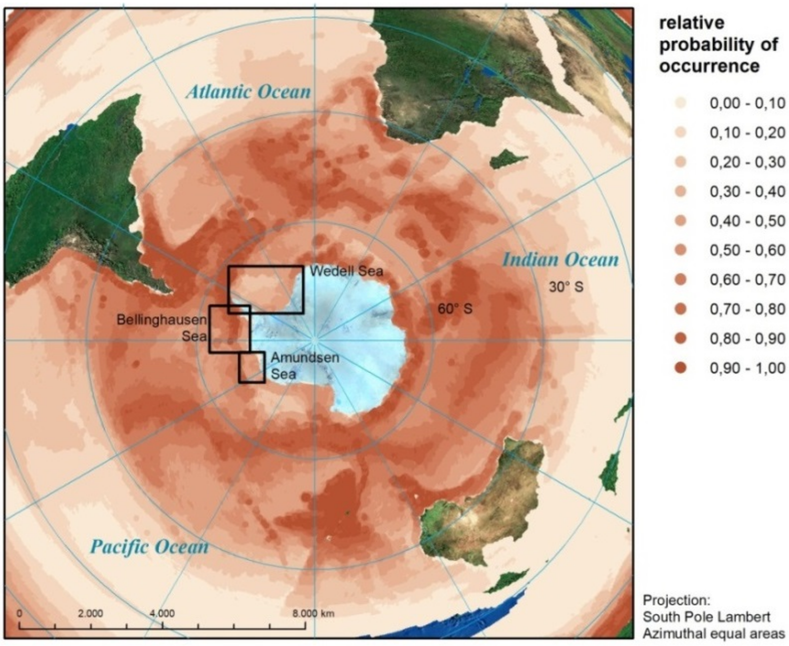
Order	Cetacea
Suborder	Mysticeti
Family	Balaenopteridae
Species	*Balaenoptera acutorostrata subspecies*

Although dwarf minke whales are visually quiet easily distinguishable by a white braid on the flipper and a dark shoulder blaze, the unnamed subspecies was only recently regarded as separated from Antarctic minke whales (Best 1985; Arnold et al. 2005). They are assigned provisionally to the single species *B. acutorostrata* (Reilly et al. 2008e). At sea differentiation shows to be difficult, resulting in a large number of unidentified species assignments during surveys (Acevedo et al. 2010). Dwarf minke whales, although much lower in number compared to Antarctic minke whales, were observed for instance around the south Shetlands, the Gerlache Strait (in austral summer) and in the Bellingshausen Sea (in austral winter) around the Antarctic Peninsula (Acevedo et al. 2010). This suggests that the subspecies uses low latitudes and some individuals stay in Antarctica during austral winter.

Minke whales, including the ‘dwarf’ form, feed on myctophid fishes and krill, but the diet varies with season and area. Generally minke whales are diverse feeders (Perrin and Brownell 2009) but show preferences for fish rather than plankton and krill (Skaug et al. 1997). Kato and Fujise (2000) found mainly myctophid fish in 16 Antarctic dwarf minke’s, while Secchi (2003) reported only *Euphausia similis* in the stomach of one animal on the coast of Brazil.

They are usually found alone or in small groups with a maximum of two or three animals. However, it was also reported that there are groups of up to 400 animals in high latitudes (Perrin & Brownell 2009).

Fig. 4-9 Native distribution map of dwarf minke whales in the Southern Ocean[11], only areas in brown to white shades are modelled outcome, blue areas are not included in the model.



The global population of minke whales is estimated at 182,000 individuals and is stable. There are no data on the abundance of dwarf minke whales in the Antarctic waters because of the difficult species differentiation at sea. Minke whales (*B. acutorostrata*) are listed in the IUCN Red List as "Least Concern" (Reilly et al. 2008e).

Table 4-4 Parameters of vocalisations of minke whales including northern hemisphere sounds

Signal type	Frequency range (Hz)	Frequency near Maximum Energy (Hz)	Dominant frequencies (Hz)	Source level (dB re 1 µPa at 1 m)	References
sweeps, moans*	60-140			151-175	Wartzok and Ketten (1999)
Downsweeps*	60-130			165	Schevill and Watkins (1972)
moans, grunts*	60-140	60-140	60-140	151-175	Schevill and Watkins (1972); Winn and Perkins (1976)
ratchet*	850-6,000	850	850		Winn and Perkins (1976); Wartzok and Ketten (1999)
clicks*	3,300-20,000		<12.000	151	Beamish and Mitchell (1973); Winn and Perkins (1976)
thump trains	100-2,000	100-200	100-200		Winn and Perkins (1976);

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[11] Computer Generated Native Distribution Map of Balaenoptera acutorostrata (reviewed). www.aquamaps.org, version of Aug. 2010. Web. Accessed 14 Aug. 2012. Expert remarks: Predicted occurrence shows positive correlations with sighting data. Minor modification of temperature and primary production cut-offs to capture this species´ maximum ranges. Distribution is a compromise between summer and winter ranges (species has very different depth preferences during different stages of annual life). Probably false predicted presence in Hudson´s Bay, North Sea, Sea of Japan, Yellow Sea and Sea of Okhotsk. 2009-09-10, Kristin Kaschner

Signal type	Frequency range (Hz)	Frequency near Maximum Energy (Hz)	Dominant frequencies (Hz)	Source level (dB re 1 µPa at 1 m)	References
(also pulsed trains)*					
"boing"	1,300-5,000			150	Ranking and Barlow (2005)
"star-wars"	50-9,400			150-165	Gedamke et al. (2001)

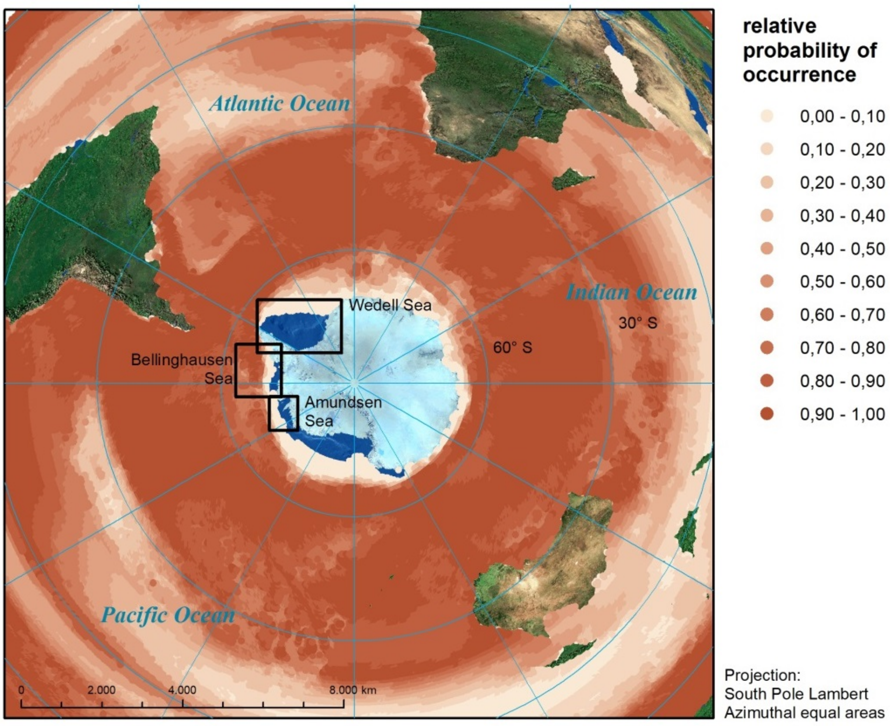
* General data for Minke whales irrespective of species

4.1.6 Humpback Whale

Order	Cetacea
Suborder	Mysticeti
Family	Balaenopteridae
Species	*Megaptera novaeangliae*

Humpback whales undertake long seasonal migrations with distances of over 8,000 km (Stone 1990) from their summer feeding areas to winter breeding grounds (Clapham 2009; Stevick et al. 2004; Winn and Reichley 1985). Some overlap between northern and southern hemisphere individuals may exist (Acevedo and Smultea 1995). While the IWC has acknowledged seven breeding areas and six associated feeding areas in the southern hemisphere, exchange within these areas is likely and the amount of separation is not fully understood (Clapham 2009). The species distribution reaches into circumpolar regions in austral summer, but does not penetrate into the ice as much as for minke and blue whales (Kasamatsu et al. 1996). With the beginning of November encounter rates increase with a maximum in January (Kasamatsu et al. 1996). Maximum encounter rates in Antarctic waters close to the Antarctic Peninsula are found between 62-66°S and 60-80°W, but encounters can also occur close to the pack ice (Kasamatsu et al. 1996).

Fig. 4-10 Native distribution map of humpback whales in the Southern Ocean[12], only areas in brown to white shades are modelled outcome, blue areas are not included in the model.



Humpback whales feed on euphausiids and small schooling fish (Clapham 2009). They have developed specialized feeding strategies including the use of air bubble nets to trap schooling fish (Baraff et al. 1991; Hain 1982). Large aggregations of humpback whales can be found in areas of high krill occurrence (Nowacek et al. 2011).

Humpback whales form social groups with up to seven individuals, within groups mother calf pairs are sometimes escorted by males (Winn and Reichley 1985). Baraff (1993) describes that the separation between mother and calf can occur prior to the calf's first winter.

The population of humpback whales was severely depleted due to hunting but seems to be increasing now, at least in parts of the northern hemisphere (Stevick et al. 2003). In the Southern Ocean about 42,000 animals were estimated in 1997/98 (Branch 2006b). For management reasons 6 breading stocks (BS) have been established (A-G) which seem to be consistent with genetic data (Pastene et al. 2006). BSA (Breeding Stock A) coincides with the Weddell Sea, BSG with the Amundsen Sea, and BSF with large parts of the Bellingshausen Sea as winter feeding habitats. Abundance was reported to be 6,250 individuals (95 % CI = 4,500 – 8,800) (Andriolo et al. 2006; Leaper et al. 2008a) for BSA with an estimated growth rate of 7.4 % per year (95 % CI 0.5-14.5 % per year; Ward et al. 2006). The estimate of 6,250 animals would correspond to approximately 28 % of pre-exploitation abundance (Zerbini et al. 2006). For BSG feeding grounds the abundance estimate ranged from 1,800 to 6,700 individuals (Leaper et al. 2008a), but most surveys only covered parts of the feeding grounds and are thus not representative for the popula-

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[12] Computer Generated Native Distribution Map of Megaptera novaeangliae (reviewed). www.aquamaps.org, version of Aug. 2010. Web. Accessed 14 Aug. 2012. Expert remarks: Good match with known species´ distribution. Probably false predicted occurrence in Hudson´s Bay and the Red Sea. Predicted occurrence is a compromise between summer and winter distribution. 2009-09-10. Kristin Kaschner

tion with a proposed increase of 4.6 % (95 % CI -3.4 % - 12.6 % per year; Branch 2006b, 2011). BSF is separated into two breeding stocks (Cook Islands – 1 and French Polynesia – 2; Leaper et al. 2008a). For BSF1, no current abundance estimate exists, while for BSF2 the abundance was estimated at 3,800 whales (95 % CI 2,500-6,000; Leaper et al. 2008a). For BSF the estimated rate of increase has wide confidence intervals and hence does not conclusively show whether there is an increase, a stable population or a decrease (Leaper et al. 2008a).

The very diverse vocal repertoire of humpback whales consist of moans, groans, cries, squeals, chirps and clicks (e.g. Au et al. 2006; Cato 1991; Darling et al. 2006; Eriksen et al. 2005; Helweg et al. 1990; Vu et al. 2012; Winn and Reichley 1985; Winn et al. 1981). Song occurs in breeding (Darling et al. 2006) and feeding (Clark and Clapham 2004) areas.

McCauley et al. (1998) showed that aversive behaviour of humpback whales towards airgun-arrays was observed within 1 km for 20 cubic inch (0.328 L) airgun and 3 km for a larger array configuration (2678 cubic inch = 43.885 L). Small changes in dive patterns were recorded during exposure to a signal used during the ATOC (Acoustic Thermometry of the Oceans Climate) project (Frankel and Clark 2000). Recently Risch et al. (2012) documented changes in humpback song during emission of a low frequency signal (peak frequencies: 415, 735 and 950 Hz) of the Ocean Acoustics Waveguide Remote Sensing (OAWRS) experiment in 200 km distance. Humpback whale songs were less often registered during the transmission of the OAWRS signal.

Humpback whales are listed in the IUCN Red List as "Least Concern" (Reilly et al. 2008f).

Table 4-5 Parameters of vocalisations of humpback whales

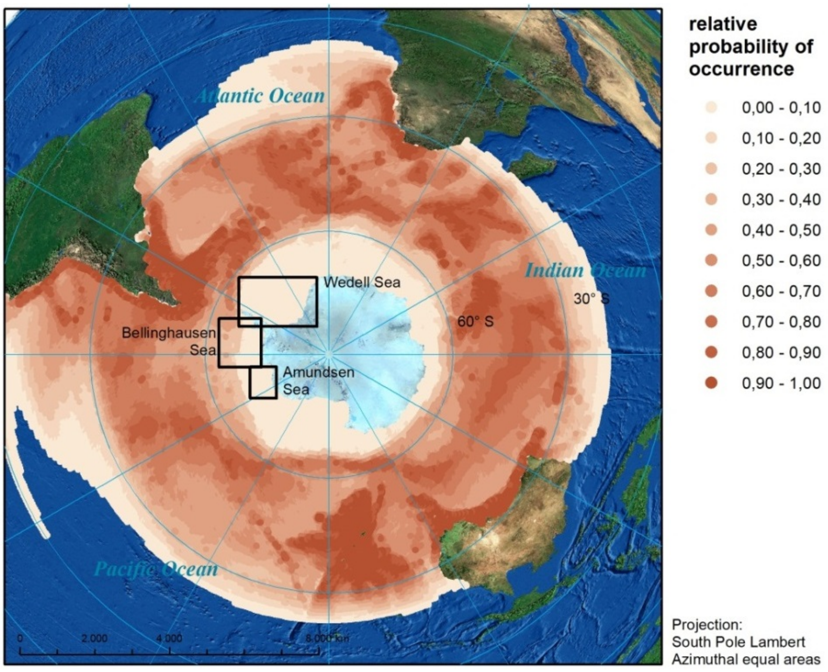
Signal type	Frequency range (Hz)	Frequency near Maximum Energy (Hz)	Dominant frequencies (Hz)	Source level (dB re 1 µPa at 1 m)	References
song	30-8,000	100-4,000	120-4000	144-186 144-174	Thompson et al. (1979); Payne and Payne (1985); Wartzok and Ketten (1999)
social	50-10,000	<3,000			Wartzok and Ketten (1999)
shrieks		750-1,800	750-1,800	179-181	Thompson et al. (1986)
horn blasts		410-420	410-420	181-185	„
moans	20-1,800	35-360	35-360	175	„
grunts	25-1,900			190	„
pulse trains	25-1,250	25-80	25-80	179-181	„
underwater blows	100-2,000			158	Beamish (1979)
fluke & flipper slap	30-1,200			183-192	Thompson et al. (1986)
clicks	2,000-8,200	1,700		143-154 (zero to peak)	Winn et al. (1970); Beamish (1979)

4.1.7 Southern Right Whale

Order	Cetacea
Suborder	Mysticeti
Family	Balaenidae
Species	*Eubalaena australis*

Southern right whales have a circumpolar distribution and were severely hunted during whaling times, because they were the 'right' whale to hunt – relatively slow, easy to catch, floating when dead and yielding large amounts of oil and baleen (Kenney 2009). The overexploitation of northern right whales in the northern Atlantic and Pacific resulted in larger effort in the southern hemisphere towards the end of the 18th century (Cummings 1985). Between 1770 and 1900 more than 150,000 right whales were hunted (Leaper et al. 2008a). While especially the North Atlantic and North Pacific right whales are among the most threatened marine mammal species, the southern right whales seem to recover from whaling (Leaper et al. 2008a).

Fig. 4-11 Native distribution map of southern right whales in the Southern Ocean[13], only areas in brown to white shades are modelled outcome, blue areas are not included in the model.



Analysis of aerial surveys showed that the distribution of southern right whales can be easily predicted around South Africa, as they seek shelter in this breeding ground. Mother calf pairs were observed closer to shore (Elwen and Best, 2004a, 2004b). Southern right whales prey on

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[13] Computer Generated Native Distribution Map of Eubalaena australis (reviewed). www.aquamaps.org, version of Aug. 2010. Web. Accessed 14 Aug. 2012. Expert remarks: Good correlation with known species´ distribution. Modification of temperature and sea ice concentration range to capture this species´ maximum range extents. Predicted range is too far south at the west coast of South America, false predicted absence from the coast of Mozambique. There are conflicting information about the southern limit of range. Predictions are a compromise between summer and winter distributions and would be improved by the use of seasonal predictions. 2009-11-21, Kristin Kaschner

krill (mainly *Euphausia superba* (Cummings 1985)), copepods, and other crustaceans (Kenney 2009).

There is little data available on the abundance. Last southern hemisphere wide estimate in 1997 resulted in 7,500 individuals (Leaper et al. 2008a) while the original population size before exploitation may have consisted of 55,000 to 70,000 individuals (IWC 2001).

Four breeding colonies are currently distinguished: Eastern South America, South Africa, Australia/New Zealand and western South America (Chile/Peru). Amundsen/Bellingshausen and Weddell Sea are most probably associated with the the eastern and western South America breeding colonies, but habitat suitability is generally low (Fig. 4-11). Abundance estimates for those breeding grounds exist from aerial surveys (Vermeulen and Cammareri, 2012) and photo identification (Brandão et al. 2012), but do not add information for the feeding grounds closer to Antarctica. The stock in eastern South America seems to be increasing at a rate of 6.9 % per year, while the western stock is low in abundance with probably less than 50 individuals and uncertain population growth (reviewed in Leaper et al. 2008a). Some exchange may exist between animals from the Scotia Sea, usually breeding on the coast of Argentina with animals breeding on the coast of South Africa (reviewed in Gill and Evans 2002). There are strong indices, that global climate has an influence on population dynamics in southern right whales (Leaper et al. 2006).

The general population size is increasing. Southern right whales are hence listed in the IUCN Red List as “Least Concern” (Reilly et al. 2008g). One major threat for right whales in general are ship strikes by fast moving large vessels (Kenney 2009; Vanderlaan et al. 2008; Ward-Geiger et al. 2005).

Right whales communicate at low frequencies (Clark 1982). In high traffic areas ship noise may induce chronic stress for North Atlantic right whales (Rolland et al. 2012). Ship noise can also lead to a shift in the communication frequency and reduced usage of vocalisation (Parks et al. 2007a).

Table 4-6 Parameters of vocalisations of southern right whales

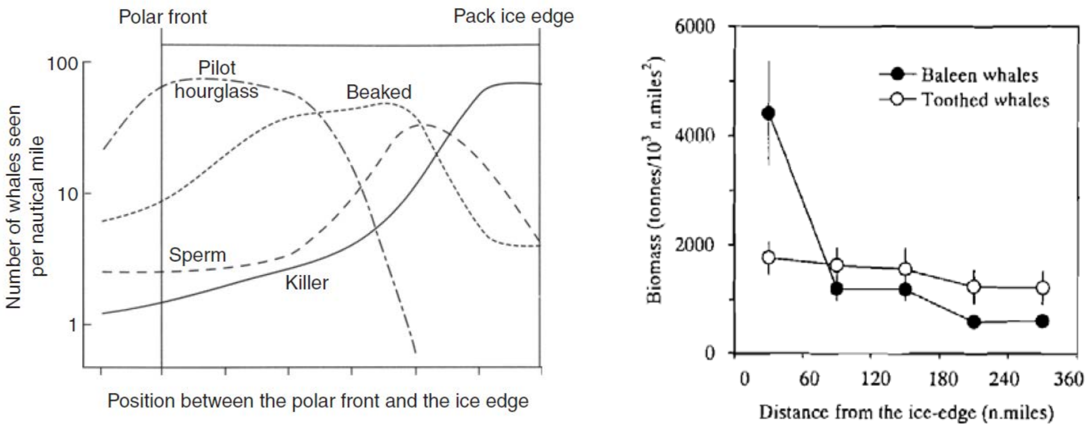
Signal type	Frequency range (Hz)	Frequency near Maximum Energy (Hz)	Dominant frequencies (Hz)	Source level (dB re 1 μPa at 1 m)	References
tonal	30-1,500	160-500			Cummings et al. (1972); Clark (1982), (1983)
tonal, mainly moans	30-1,500	160-500		182	Payne and Payne (1971)
pulsive	30-2,200	50-500		172-187 181-186	Cummings et al. (1972); Clark (1982), (1983) Clark (in Würsig et al. (1982))
broadband (blows and slaps)	50-1,000				Clark (1982)

4.2 Odontocetes

Species considered in this review are sperm whales (*Physeter macrocephalus* or older: *catodon*), killer whales (*Orcinus orca*), southern long-finned pilot whales (*Glopicephala melas edwardii*), Hourglass dolphins (Lagenorhychus cruciger) and four species of beaked whales: southern bottle-nose whales (*Hyperoodon planifrons*), Arnoux's beaked whale (*Berardius arnuxii*), strap-toothed whales (*Mesoplodon layardii*), Gray's beaked whale (*Mesoplodon grayi*) in accordance with Leaper et al. (2008b). Cuvier's beaked whales (*Ziphius cavirostris*) have also been reported south of 60°S, but not on a regular basis (Gill and Evans, 2002) and are consequently not considered within this review.

In general the knowledge about abundance and distribution of odontocetes in Antarctic waters is less reliable than for baleen whales (Leaper et al. 2008b). This is partly due to the fact that some of the odontocetes are deep divers (like beaked whales, spending only a fraction of their life on the water surface) or react towards an observation vessel (like hourglass dolphins who are known to swim towards vessels), hence strongly violating the assumptions for distance sampling strategies (visibility on the transect line and no reaction towards the surveyor) from large vessels (Leaper et al. 2008b). Some caveats originally assessed for minke whale abundance estimates in Antarctica are given and discussed in Branch (2006c). Another question arising is the representativeness of circumpolar population estimates south of 60°S for species with a more complex ecological behaviour like sperm whales, where mostly males migrate in latitude higher than 60°S (Leaper et al. 2008b) or killer whales, where three ecotypes were identified that relate differently to the ice edge (Andrews et al. 2008; Pitman et al. 2007a). According to Smith et al. (2005) passive acoustic surveys with towed hydrophones will play a major part in abundance estimation, as detection rates may increase compared to visual surveys for difficult to observe species.

Fig. 4-12 Left: Occurrence of odontocetes in Antarctica; right: total biomass of baleen and toothed whales



Left: Occurrence of odontocetes in Antarctica in relation to the pack ice edge (taken from Boyd (2009a) reprinted from Kasamatsu and Joyce, 1995); right: total biomass of baleen and toothed whales in relation to the ice-edge (taken from Kasamatsu, 2000).

Killer whales are strongly associated with the pack ice edge (Fig. 4-12), which is in accordance with their proposed correlation between minke and killer whale occurrences (Kasamatsu et al. 2000). The other two Delphinids, the hourglass dolphins and the long-finned pilot whales avoid the ice edge. Sperm whales are also found closer to the pack ice, while beaked whales show an intermediate occurrence pattern.

In whaling times especially sperm whales were hunted and their numbers were reduced drastically from thought 2-3 million individuals (Leaper et al. 2008b). Smaller odontocetes, like southern bottlenose whales, Arnoux's beaked whales and killer whales were also hunted, for instance by Japanese and Russian whalers (Kasuya 2009a), but those takes were mostly opportunistic (Leaper et al. 2008b). Odontocetes in Antarctica show different seasonal patterns, but for most species the maximum encounter rate can be registered in January, except for hourglass dolphins, where the maximum is reached in February or probably even later (Fig. 4-13; Kasamatsu and Joyce, 1995). From three circumpolar abundance estimates only killer whales showed a significant reduction in abundance, but that might be due to methodological differences between the first and second set of surveys (Fig. 4-14, Leaper et al. 2008b).

Fig. 4-13 Seasonal occurrence of Antarctic odontocetes; areas indicate mean encounter rate by month, open circles mean encounter rater per half month and standard error (from Kasamatsu and Joyce, 1995)

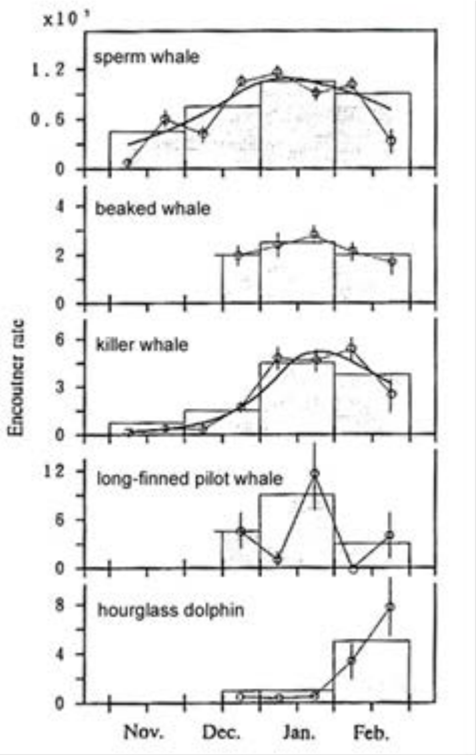
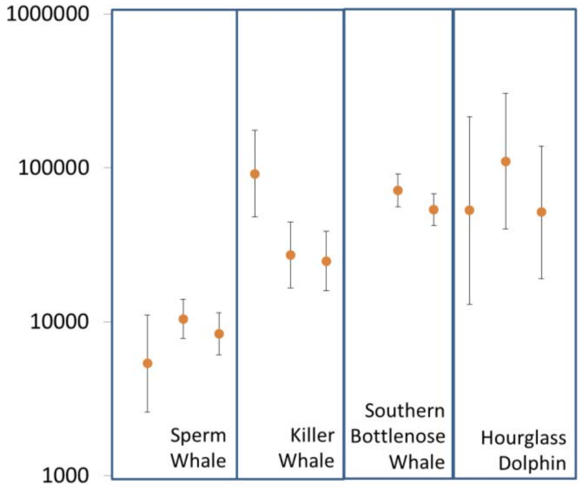


Fig. 4-14 Abundance estimates plotted from three circumpolar surveys (Branch and Butterworth, 2001; Leaper et al. 2008b) for sperm whales, killer whale, southern bottlenose whales and hourglass dolphins. Sperm whales have the lowest abundance of these species. For southern bottlenose whales no abundance estimate was calculated for the first survey set, as beaked whales were not identified on species level. Data for hourglass dolphins was excluded from Branch and Butterworth (2001) due to concerns about their validity. Note: logarhithmic y-axis.



4.2.1 Beaked Whales

Abundance estimation for beaked whales is a very difficult task, as there are only faint differences between species and according to Barlow and Gisiner (2006) mitigation monitoring during seismic operations detects fewer than 2 % when animals are directly on the path of the vessel. Branch and Butterworth (2001) showed that of three major circumpolar survey sets of the IWC only 5 %, 60 % and lastly 71 % of beaked whales sightings were attributed to species level (Leaper et al. 2008b). One common practice is to pool all beaked whales into one class (Kasamatsu 2000) or only produce an estimate for the dominant species (Branch and Butterworth 2001). Average sighting rates for beaked whales except of southern bottlenose whales are below one group per year (Leaper et al. 2008b).

To close knowledge gaps Barlow et al. (2005) suggested three future research topics:

c) Population structure: genetics, morphology, photo-identification and long term tagging studies

d) Distribution: training observers for accurate species identification at sea and collection of genetic or other material from stranded animals

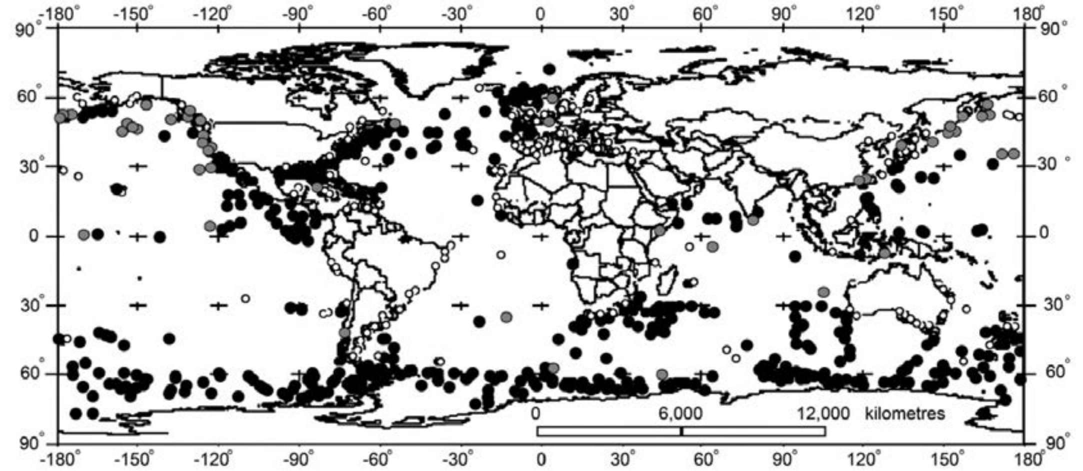
e) Estimation of correction factors for line-transect surveys for abundance estimates.

These issues are not only difficult to assess, but also take considerable time and effort. As stranding reports of beaked whales have been linked to a number of loud acoustic events like ship noise, military low and mid frequency sonar and seismic surveys, beaked whales seem to be specifically vulnerable to noise effects (Soto et al. 2006; Barlow and Gisiner 2006; Cox et al. 2006; Johnson and Tyack 2004.; Taylor et al. 2004).

Beaked whales have been found stranded with evidence for decompression sickness (Cox et al. 2006; Fernández et al. 2005; Jepson et al. 2003, 2005) probably related to shallower than usual dives (Zimmer and Tyack, 2007). These events seem to be tightly linked to naval sonar exercises (Tyack et al. 2011).

Beaked whale sightings are common in the Bellingshausen and Amundsen Seas, but not in the Weddell Sea (Fig. 4-15). Most of these sightings are southern bottlenose whales. Beaked whales have not been hunted as a primary target species.

Fig. 4-15 Distribution of beaked whale occurrence



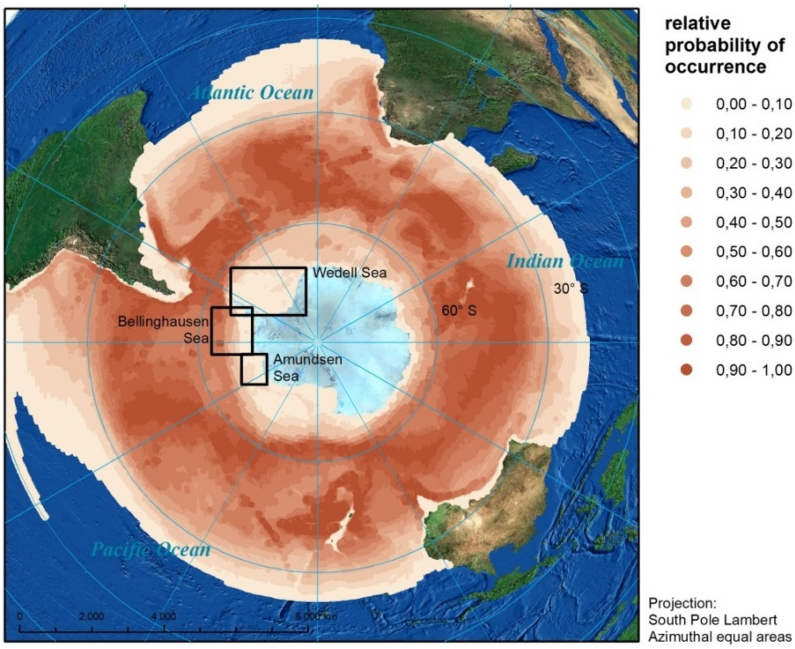
4.857 records, white – stranding, black – sighting, grey – other from MacLeod and Mitchell (2006).

4.2.1.1 Arnoux Beaked Whale

Order	Cetacea
Suborder	Odontoceti
Family	Ziphiidae
Species	*Berardius arnuxii*

Arnoux's beaked whales and Baird's beaked whales were long thought to be the same species, but genetic analyses have shown that a separation on species level is valid (Dalebout et al. 2004a; Dalebout 2002) even though genetic and morphological differences are small (Taylor et al. 2008a). Their distribution is associated with shallow areas in coastal waters or continental shelf and seamounts in cold and deep sub-polar waters and seems to be sympatric with southern bottlenose whales (Taylor et al. 2008a). Most probably they have a circumpolar distribution (Fig. 4-16) with occurrence peaks between 78°S and 34°S (Reeves et al. 2008). Even though little is known on migration patterns they are found closer to the ice-edge in summer, while they are likely to move further away in winter (Culik, 2004). Some animals nevertheless may get trapped by ice and may overwinter closer to Antarctica (Reeves et al. 2008).

Fig. 4-16 Native distribution of Arnoux beaked whale in the Southern Ocean[14], only areas in brown to white shades are modelled outcome, blue areas are not included in the model.



Presumably they feed on squid and deep sea fish (Reeves et al. 2008) and were observed in larger groups along the ice-edge (Ponganis et al. 1995). They may be able to use prey inaccessible to other predators in ice-covered waters due to their ability to find breathing sites far apart using

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[14] Computer Generated Native Distribution Map of Berardius arnuxii (reviewed). www.aquamaps.org, version of Aug. 2010. Web. Accessed 14 Aug. 2012. Expert remarks: Relatively good fit with known species´ occurrence, although there are large areas of potentially false predicted presences (too far north along the coast of South Africa and west coast of South America?). Adjustment of maximum temperature, salinity and sea ice concentration envelopes to capture all known northern sighting records. 2010-04-09, Kristin Kaschner

long duration dives (Culik 2004). Arnoux's beaked whales live in schools (Kasuya 2009b). Animals were recorded acoustically around the Antarctic Peninsula, suggesting that group sizes are around 7 individuals (Rogers and Brown 1999).

There is little information on the abundance, distribution and trends of Arnoux's beaked whales, but the species is potentially vulnerable. Hence they are classified in the IUCN Red List as "data deficient" (Taylor et al. 2008a).

Sightings of *B. arnuxii* are rare events, but do occur close to the ice-edge (Fig. 4-17). Knowledge on vocalisations is scarce (Table 4-7 below).

Fig. 4-17 Records of *Berardius spp.* (from MacLeod et al. 2006

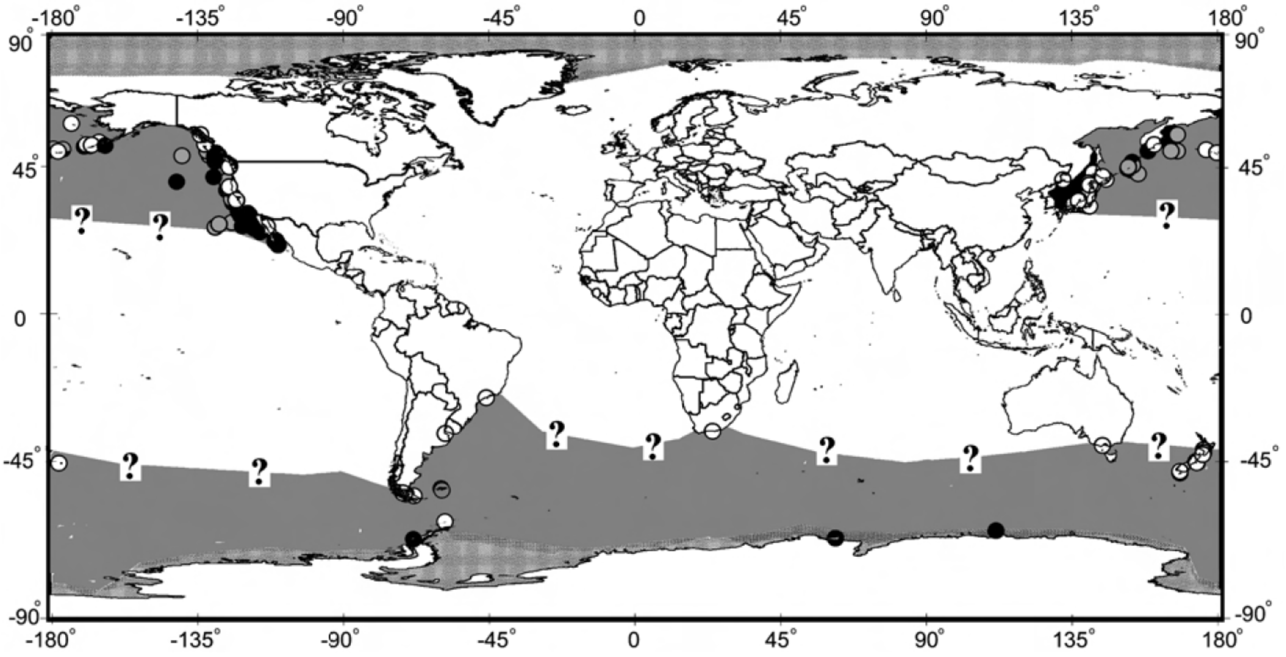


Table 4-7 Parameters of vocalisations of Arnoux's beaked whale

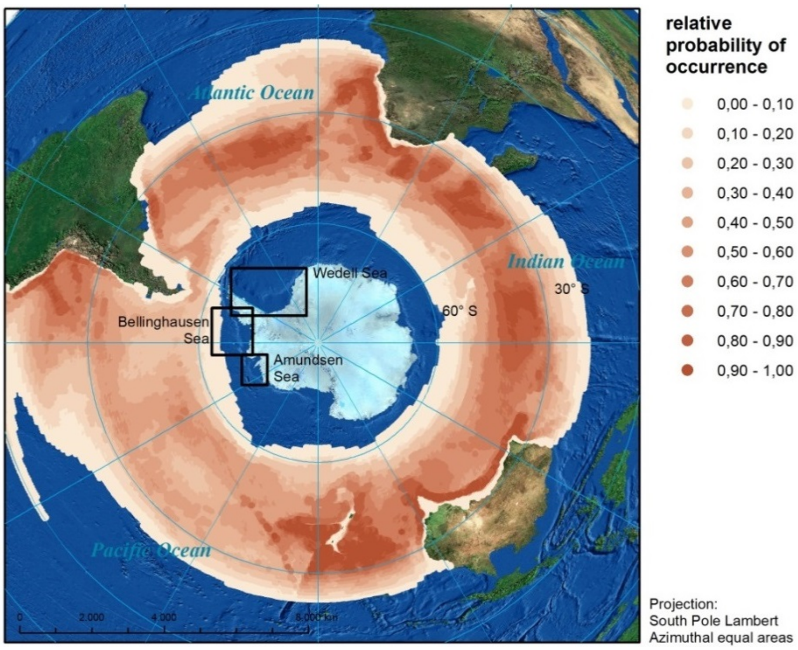
Signal type	**Frequency range (Hz)**	**Frequency near Maximum Energy (Hz)**	**Dominant frequencies (Hz)**	**Source level (dB re 1 µPa at 1 m)**	**References**
amplitude-modulated calls	1,000-8,500	1,500-4,600 5,600			Rogers and Brown (1999)
whistles	2,000-6,000	4,300-4,900 5,200[1]			"
clicks	12,000-18,000				"

4.2.1.2 Strap-Toothed Whale

Order	Cetacea
Suborder	Odontoceti
Family	Ziphiidae
Species	*Mesoplodon layardii*

Strap-toothed whales are also called Layard's beaked whales. They show a circumpolar distribution between 30°S and the Antarctic Convergence (Fig. 4-18), but do not migrate as close to the ice-edge as the southern bottlenose whales and Arnoux's beaked whales. According to Pitman (2009), strap-toothed whales are one of the largest and widely distributed mesoplodont whales in the temperate and subantarctic southern hemisphere. Due to their name-giving teeth they are only able to feed on smaller squid (Reeves et al. 2008). They are thought to be deep divers and prefer deep waters. Potentially they undertake seasonal migrations as indicated by seasonally varying stranding patterns (Taylor et al. 2008b).

Fig. 4-18 Native distribution of strap-toothed whale in the Southern Ocean[15], only areas in brown to white shades are modelled outcome, blue areas are not included in the model.



There is little information available on the abundance of strap-toothed whales but it is probably not as rare a species as indicated by sighting records (Fig. 4-19).

Strap-Toothed Whales are not classified in a conservation status in the IUCN Red List (category "data deficient"; Taylor et al. 2008b).

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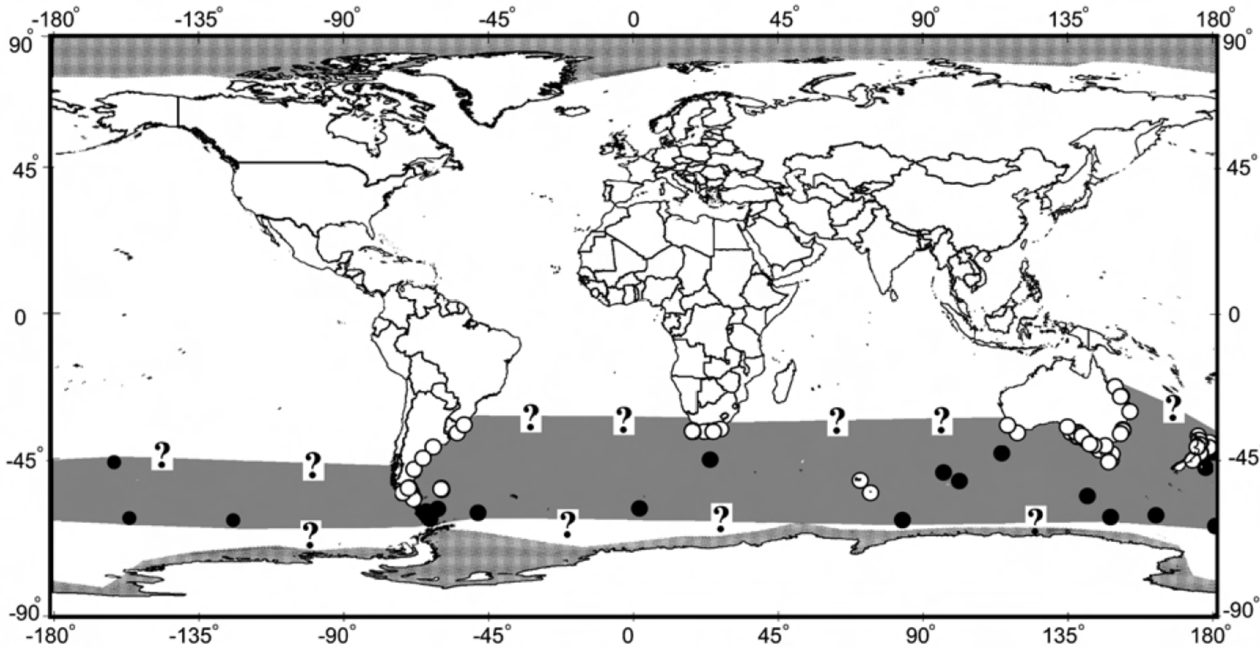
[15] Computer Generated Native Distribution Map of Mesoplodon layardii (reviewed). www.aquamaps.org, version of Aug. 2010. Web. Accessed 14 Aug. 2012. Expert remarks: Test of predictions showed positive correlation with observed stranding patterns, but quality is difficult to assess due to given low sample size. Predictions based on new SST and ice data are very similar based on visual comparisons, but have not been re-tested. Large areas of probably false predicted presences (e.g., west coast of South America?) or absences (e.g., not far enough south?). 2009-11-23, Kristin Kaschner.

There is currently no knowledge about strap-toothed beaked whale vocalisations.

Fig. 4-19 Records of strap-toothed whales (from MacLeod et al. 2006)



4.2.1.3 Southern Bottlenose Whale

Order	Cetacea
Suborder	Odontoceti
Family	Ziphiidae
Species	*Hyperoodon planifrons*

Southern bottlenose whales show a circumpolar distribution, most commonly south of 30°S up to 73°S in the Ross Sea (Reeves et al. 2008, Fig. 4-20). Knowledge on seasonal migration comes mostly from whaling times and it is unclear whether the recorded patterns are actually seasonal variation in animal occurrence or if they are associated to the whalers routes to the Antarctic (Gowans 2009). Research regarding group composition has mainly been carried out on northern bottlenose whales; the so called ‚Gully' population[16]. Associations in fission-fusion groups are mainly brief, but adult males are found to have long-term companionships with unknown function (Gowans et al. 2001). Group size is usually 1-4 animals, larger groups are uncommon, but often more than one group can be seen within smaller areas (Mead 1989). In contrast to other beaked whale species these animals are curious and approach boats (Mead 1989).

Southern bottlenose whales are the only beaked whale species where abundance estimates are available. During the second and third circumpolar IDCR/SOWER surveys, it was established that 71,560 individuals (95 % CI 56,000-91,400) were estimated from 1985-91 and 53,743 individuals (95 % CI 42,400-68,100) were estimated from 1991-98 (Branch and Butterworth 2001; Leaper et

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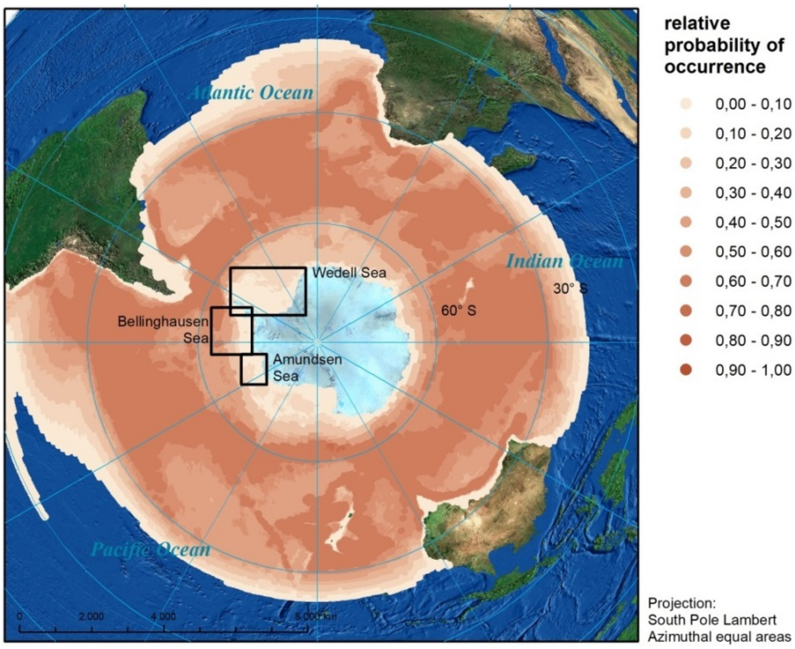
[16] Gully is a submarine canyon on the edge of the Scotian Shelf, with a high percentage of the bottlenose whales being photographically identified.

al. 2008b). These estimates are most probably an underestimate of real population size due to the species long dives and therefore an underestimation of g(0) – the detection probability on the transect line. With a modelled g(0) of 0.27 Kasamatsu and Joyce (1995) calculated 599,300 individuals. There is no known trend in abundance for this species.

Fig. 4-20 Native distribution of southern bottlenose whales in the Southern Ocean[17], only areas in brown to white shades are modelled outcome, blue areas are not included in the model.



Southern bottlenose whales are listed in the IUCN Red List as “Least Concern” (Taylor et al. 2008c). Sightings are mostly concentrated around the ice-edge, but accumulations on the western Antarctic Peninsula are quite common (Fig. 4-21; MacLeod et al. 2006).

Reports on vocalisations are scarce (Table 4-8). There are some recordings of northern bottlenose whales, but it is unclear if they are representative for southern bottlenose whales as well (Winn 1970 in Mead 1989). They ranged from 3 to 16 kHz and consisted of whistles, chirps, burst-pulse tones and clicks.

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[17] Computer Generated Native Distribution Map of Hyperoodon planifrons (reviewed). www.aquamaps.org, version of Aug. 2010. Web. Accessed 14 Aug. 2012. Expert remarks: Very good correspondence with known species´ occurrence. Predictions have successfully been validated using IWC Sower sightings (Kaschner et al, in press) and show strong positive correlation with observed stranding patterns (Kaschner, 2004). Predictions based on new SST very similar based on visual comparisons, but have not yet been re-tested. Adjustment of temperature, primary production and sea ice concentration envelopes. Predictions would be improved by use of seasonal predictions.2009-11-23, Kristin Kaschner.

Fig. 4-21 Records of southern bottlenose whales (from MacLeod et al. 2006)

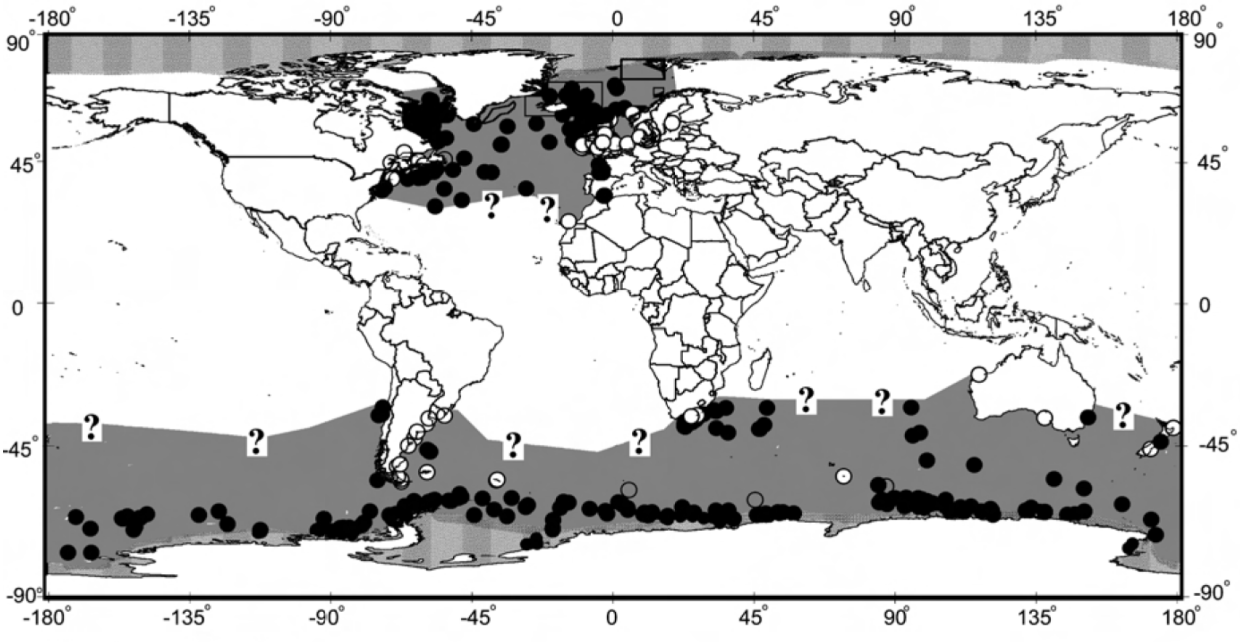


Table 4-8 Parameters of vocalisations of southern bottlenose whales

Signal type	Frequency range (Hz)	Frequency near Maximum Energy (Hz)	Dominant frequencies (Hz)	Source level (dB re 1 µPa at 1 m)	References
clicks in short bursts	18,000				Leaper and Scheidat (1998)

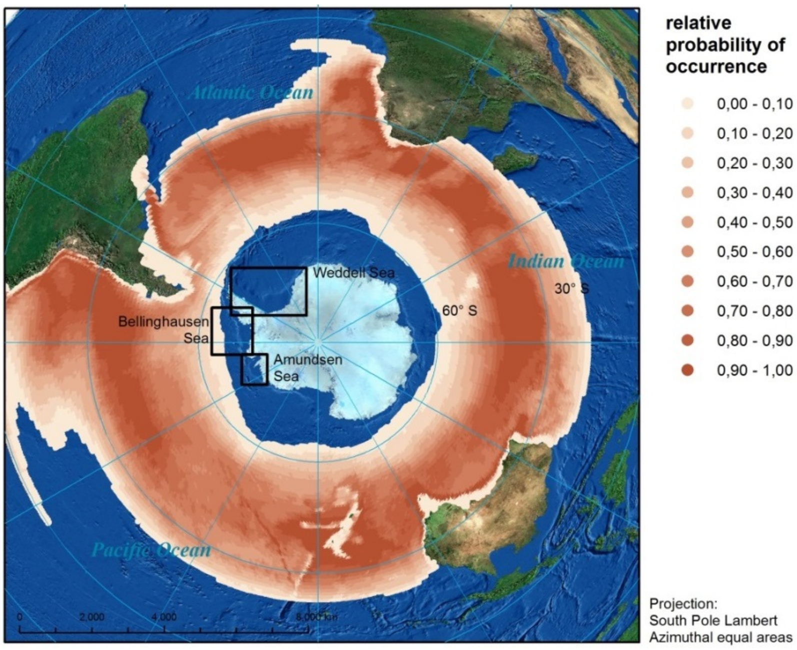
4.2.1.4 Gray's beaked whale

Order	Cetacea
Suborder	Odontoceti
Family	Ziphiidae
Species	*Mesoplodon grayi*

Generally Gray's beaked whales occur in circumpolar temperate waters of the southern Hemisphere (Pitman 2009). During austral summer they can also be detected near the shores and in the sea ice. According to most of the records and sightings Gray's beaked whales are found south of 30°S up to sub-Antarctic and Antarctic regions (Taylor et al. 2008d). Strandings and sightings indicate the zone south-west of the Chatham Islands as a hotspot area (Dalebout et al. 2004b). Fig. 4-22 shows the native range of *Mesoplodon grayi*.

Cephalopods in deep waters (200m or more) are the major food source for Gray's beaked whales (Taylor et al. 2008d; Pitman 2009). Like for other beaked whale species little is known about the social behaviour of Gray's beaked whales. Dalebout et al. (2004b) calculated a group size of 3.3 ± 1.97 individuals from sightings near New Zealand from 1985 to 2002.

Fig. 4-22 Native distribution of Gray’s beaked whales in the Southern Ocean[18], only areas in brown to white shades are modelled outcome, blue areas are not included in the model.



For Grey’s beaked whales no estimations of population size exists and therefore there is currently no known trend in the abundance. Hence they are not classified in a conservation status in the IUCN Red List but registered in the category “data deficient” (Taylor et al. 2008d).

Currently there are no vocalisation records available for Gray’s beaked whale (Erbe 2004).

4.2.2 Hourglass Dolphin

Order: Cetacea

Suborder: Odontoceti

Family: Delpinidae

Species: *Lagenorhynchus cruciger*

Hourglass dolphins show a circumpolar distribution and can be found from the ice edge to 45°S, occasionally up to 33°S (Hammond et al. 2008, Goodall 2009). The highest density of sightings is between 45 and 60° S (Goodall 2009).

An estimate from 1995 resulted in an abundance of 144,300 individuals for waters south of the Antarctic convergence (Kasamatsu and Joyce 1995). It has been observed that the abundance of hourglass dolphins in Antarctic waters starts to increase in early February. Simultaneously, the water surface temperature in this area is rising (Kasamatsu and Joyce 1995).

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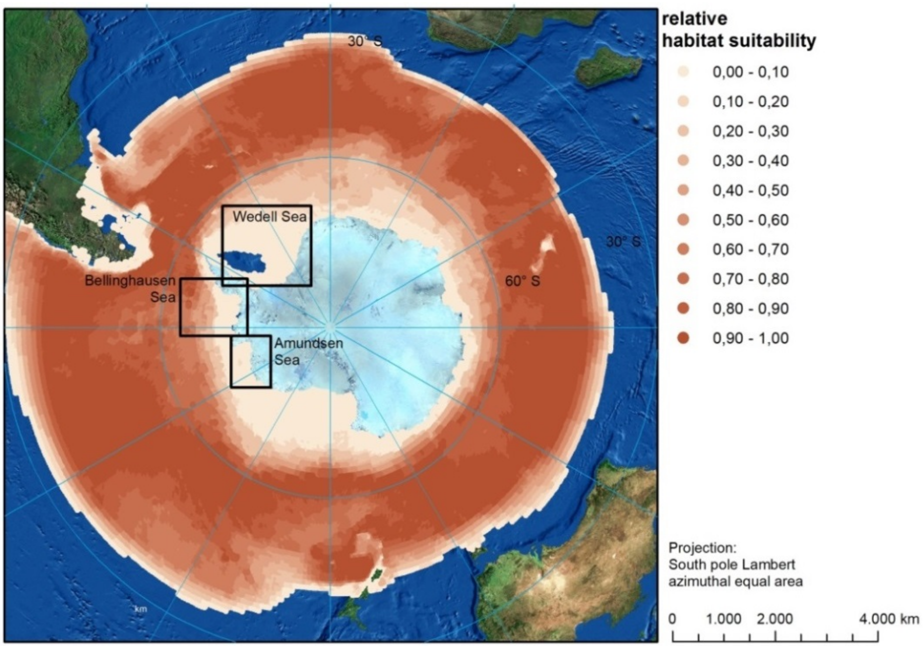
[18] Computer Generated Map for *Mesoplodon grayi* (Gray’s beaked whale). www.aquamaps.org, version of Aug. 2010. Web. Accessed 21 Feb. 2013.

Fig. 4-23 Native Distribution map of hourglass dolphins in the Southern Ocean[19], only areas in brown to white shades are modelled outcome, blue areas are not included in the model.



Hourglass dolphins prey on squid, crustaceans and small fish (Hammond et al. 2008). They frequently prey in areas with accumulations of seabirds and plankton swarms (Goodall 2009; Hammond et al. 2008). Fernández et al. (2003) reported the stomach content of two hourglass dolphins and found mainly fish and cephalopods, but also crustaceans and partly polychaetes, most probably digested by other prey.

Hourglass dolphins occur in schools of up to sixty individuals, but are more commonly seen in groups of 4 to 7 animals. Observations show that they accompany other species, for example fin whales, minke whales, large bottlenose whales, pilot whales and southern right whales (Goodall 2009).

Hourglass dolphins are listed in the IUCN Red List as “Least Concern” and there is no known trend in the abundance for this species (Hammond 2008, Leaper et al. 2008b).

Like other small delphinids hourglass dolphins produce high-frequency clicks to detect their prey (Fig. 4-24, Table 4-9).

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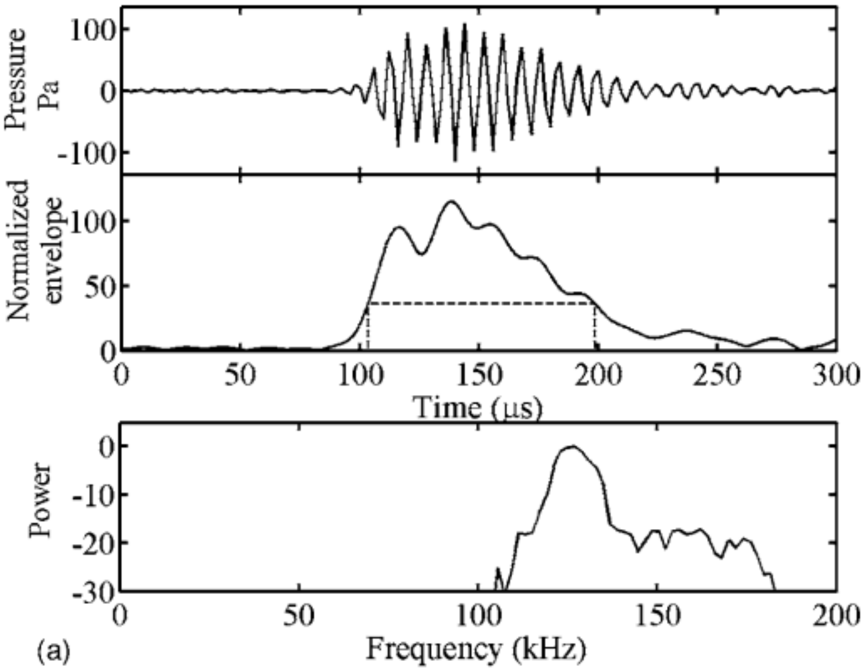
[19] Computer Generated Native Distribution Map of Lagenorhynchus cruciger (reviewed). www.aquamaps.org, version of Aug. 2010. Web. Accessed 22 Aug. 2012. Expert remarks: Test of predictions showed strong positive correlation with observed sightings in Antarctic waters (IWC SOWER survey). Predictions based on new SST and ice data are very similar based on visual comparison, but have not yet been re-tested. Adjustment of temperature and sea ice concentration envelopes. Predicted presence in northern Chile is not supported by published data and distribution might range too far south. Kristin Kaschner, 2009-11-23.

Fig. 4-24 Time domain, envelope, and power spectrum of a representative hourglass dolphin signal.



The dashed square in the envelope denotes the 10 dB duration. Fast Fourier transform (FFT) size of 256, spectrum interpolated with a factor 100, sampling rate of 500 kHz, and rectangular window (Kyhn et al. 2009).

Table 4-9 Parameters of vocalisations of hourglass dolphins

Signal type	Frequency range (kHz)	Frequency near Maximum Energy (kHz)	Dominant frequencies (kHz)	Source level (dB re 1 µPa at 1 m)	References
click	122-131	126		190-203 pp	Kyhn et al. (2009)

4.2.3 Killer Whale

Order Cetacea

Suborder Odontoceti

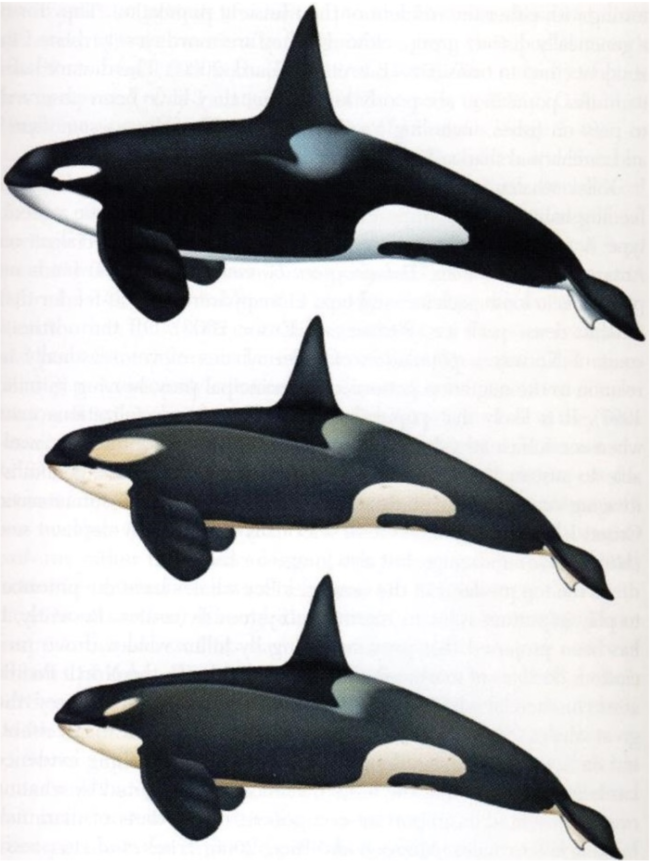
Family Delphinidae

Species *Orcinus orca*

Killer whales are distributed circumglobally (Fig. 4-26) with a preference for colder and more productive waters (Ford 2009), but also near shore (Taylor et al. 2008e). Although large differences in prey items, social habits and association with different habitats exist, only one species is acknowledged at the moment (Ford 2009; Leaper et al. 2008b). Pitman and Ensor (2003) and Pitman et al. (2007a) describe three different ecotypes separated by size, morphology, color patterns and diet. Type C inhabits dense pack-ice, is specialized on fish and is probably the smallest killer whale. It is predominantly sighted in the Ross Sea. Type A refers to larger offshore animals specialized on cetaceans as prey and commonly encountered in ice free waters

(LeDuc et al. 2008; Pitman et al. 2007a). Type B is morphologically similar, but has a larger eye patch than type C. It specializes in pinnipeds and inhabits pack-ice (LeDuc et al. 2008). Genetic analysis of these different ecotypes showed significant differences suggesting reproductive isolation, but also low sequence divergence indicating recent and rapid evolutionary changes (LeDuc et al. 2008). Type B and C killer whales may overwinter in Antarctica (Pitman and Ensor 2003).

Fig. 4-25 Ecotypes of killer whales



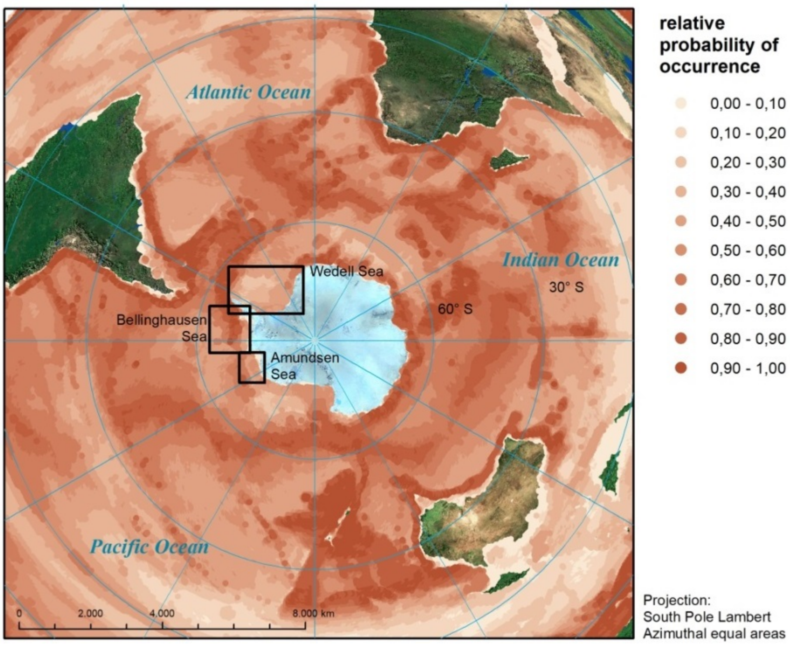
Ecotypes of killer whales in the southern hemisphere (type A on top, C on bottom, from Ford (2009), illustration by U. Gorker)

Killer whales prey on a large range of different food items, but ecotypes are linked to their prey, like the Antarctic ecotype A prefers minke whales (Reilly et al. 2008d, Ford 2009). There are also reports on predation of penguins (Lauriano et al. 2007).

The available data are inconclusive, but the worldwide population is estimated at 50.000 individuals, which is most probably an underestimate (Taylor et al. 2008e). For the Southern Ocean alone 24,790 individuals (95 % CI 15,900-38,700) were estimated during the last circumpolar survey set of IDCR/SOWER (Branch and Butterworth 2001; Leaper et al. 2008b). There is no known trend in the abundance for this species. Although differences in estimates were stated from the first two circumpolar survey sets, it remains unclear whether these differences originate from different survey strategies or are indeed due to a change in abundance (Leaper et al. 2008b). In the Weddell Sea Kasamatsu and Joyce (1995) report a gap in distribution, which is supported by the habitat prediction model showing a low suitability for the Amundsen Sea as well (Fig. 4-26). A winter sighting of a group of killer whales with a calf indicates that breeding of killer whales in Antarctica during winter in denser ice is possible (Gill and Thiele 1997).

Killer whales are classified in the conservation status in the IUCN Red List as “data deficient” due to the uncertainties regarding species declaration. If species or subspecies would be assigned, a higher conservation status would probably be indicated (Taylor et al. 2008e).

Fig. 4-26 Native Distribution map of killer whales in the Southern Ocean[20], only areas in brown to white shades are modelled outcome, blue areas are not included in the model.



Orcinus orca vocalise very actively, but show adaptations to the hearing abilities of their preferred prey items (Foote and Nystuen 2008). They are able to learn vocal patterns and mimic sounds (Deecke et al. 2005; Foote et al. 2006, 2008; Miller et al. 2004a).

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[20] Computer Generated Native Distribution Map of Orcinus orca (reviewed). www.aquamaps.org, version of Aug. 2010. Web. Accessed 14 Aug. 2012. Expert remarks: Good correspondence with known species´ occurrence. Minor modification of salinity and primary production ranges to capture this species´ maximum distribution ranges. Predicted distribution presumably constitutes a compromise between different subpopulations with different habitat preferences and between summer and winter distributions. Predicted occurrence in the Red Sea is not supported by published data. Possibly false predicted absence in the Baltic Sea. 2009-09-09, Kristin Kaschner

Table 4-10 Parameters of killer whale vocalisations

Signal type	Frequency range (Hz)	Frequency near Maximum Energy (Hz)	Dominant frequencies (Hz)	Source level (dB re 1 µPa at 1 m)	References
whistles	1,500-18,000	6,000-12,000	6,000-12,000		Steiner et al. (1979); Ford and Fisher(1983) Morton et al.(1986)
pulsed calls	500-25,000	1,000-6,000	1,000-6,000	160	Schevill and Watkins (1966); Awbrey et al. (1982) Ford and Fisher (1983) Moore et al. (1988)
clicks	250-500				Schevill and Watkins (1966)
clicks	100-35,000	12,000-25,000		180	Diercks et al. (1971), Diercks (1972)
screams	2,000				Schevill and Watkins (1966)

4.2.4 Long-finned Pilot Whale

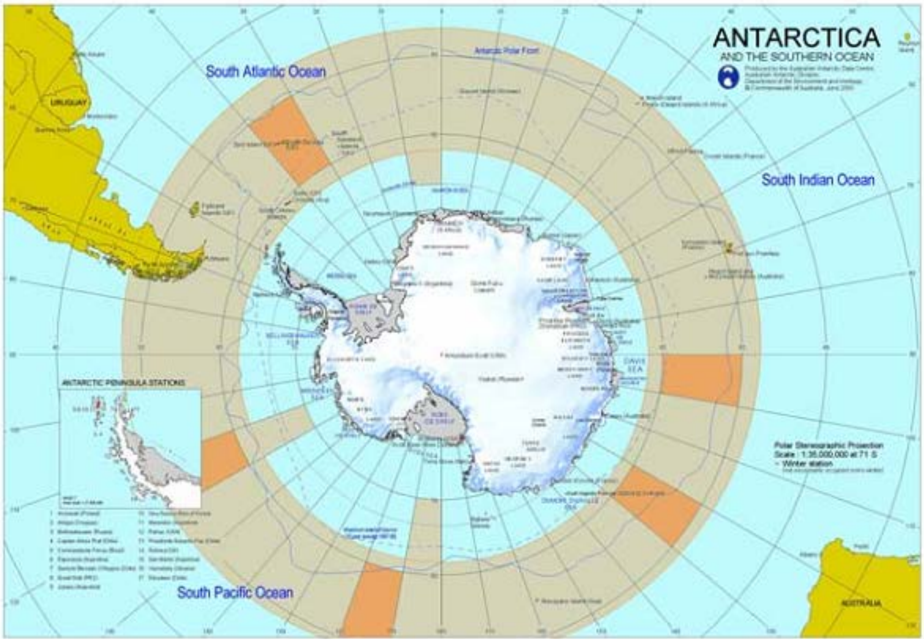
Order	Cetacea
Suborder	Odontoceti
Family	Delphinidae
Species	*Globicephala melas*
Subspecies	*Globicephala melas melas* (northern Hemisphere) *Globicephala melas edwardii* (southern hemisphere)

Long-finned pilot whales have a widespread distribution in cold temperate waters and occur in both the southern and the northern oceans (Olson 2009). *Globicephala melas melas* occurs in the north and *Globicephala melas edwardii* inhabits the southern hemisphere (Olson 2009). In Antarctic waters long-finned pilot whales show a circumpolar distribution, seem to be associated with the Antarctic Convergence and stay away from the ice-edge (Olson 2009; Taylor et al. 2008f; Boyd 2009a, Fig. 4-27, Fig. 4-28).

Their migration patterns are not very well known. Nevertheless, it has been observed that the abundance of long-finned pilot whales in the Antarctic waters is slightly increasing during the second half of January (Gill and Evans 2002).

The population is estimated at several hundred thousand, with approximately 200.000 animals ranging south of the Antarctic Convergence in summer. There is no known trend in the abundance for this species (Taylor et al. 2008f).

Fig. 4-27 Main distribution of long-finned pilot whales during the summer months.



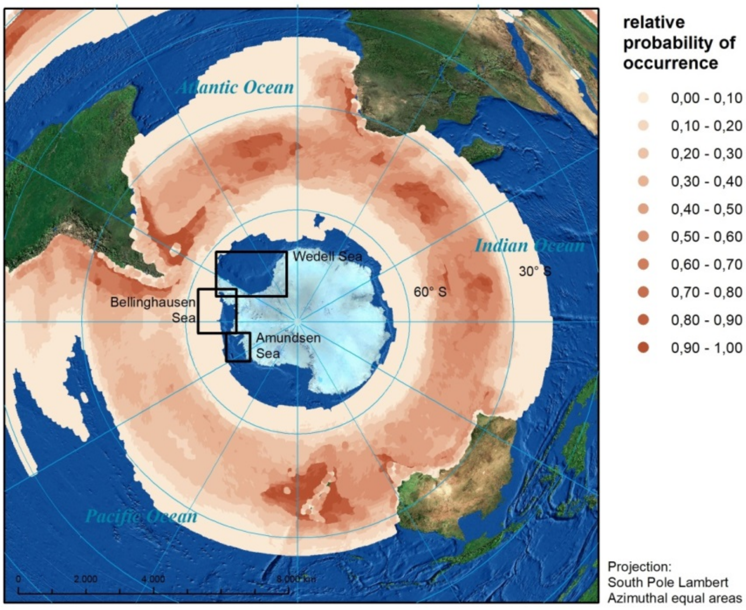
Dark areas show area of most sightings. Based on analysis by Kasamatsu and Joyce (1995) from surveys covering Antarctic waters, defined as those south of the Antarctic Convergence (AC). The AC is considered to be at 50°S between 60°W-160°E in the South Atlantic–Indian Ocean Sector and at 60°S between 160°E-60°W in South Pacific Sector (from Gill and Evans 2002).

Pilot whales have a complex social life forming pods ranging from 20-90 individuals and are travelling, foraging and logging in groups (Olson 2009). Within stable pods calfs are brought up, while adult males seem to breed with other family groups (Amos et al. 1993). It has been observed, that long-finned pilot whales are associated with other species, for example common bottlenose dolphins, short-beaked common dolphins, killer whales, sperm whales and fin whales (Olson 2009).

Long-finned Pilot whales prey mostly on squid, but they also feed on fish (mackerel, cod, turbot, herring hake, dogfish shark) and sometimes even on shrimp (Taylor et al. 2008f). Pilot whales show a diurnal diving pattern with shorter dives (1-16 m) during daytime and deeper dives (>100 m) being performed at night (Olson 2009). However, in the northeast Atlantic a long-finned pilot whale reached a maximum dive depth of 828 m (Heide-Jorgensen et al. 2002), but those data, as well as those by Baird et al. (2002) reporting longer and deeper dives during night-time, come from the northern subspecies.

Long-finned pilot whales are classified as conservation status “data deficient” in the IUCN Red List (Taylor 2008f).

Fig. 4-28 Native Distribution map of long-finned pilot whales in the Southern Ocean[21], only areas in brown to white shades are modelled outcome, blue areas are not included in the model.



Mass strandings of short- and long-finned pilot whales have been linked to different causes like possible virus infections or socially caused strandings, where ill animals are accompanied by other healthy animals (reviewed in Olson 2009).

Long-finned pilot whales use echolocation for prey catch and whistles for communication (Olson 2009, Table 4-11). Short-finned pilot whales have been reported to show avoidance reactions to a ramp-up procedure of a 2D-seismic survey for mitigation purposes (Weir 2008). The reaction was limited in time and space and animals may have spent longer time at the surface to avoid higher sound pressures deeper in the water column and therefore being unprotected by the attenuation due to the Lloyd's mirror effect.

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[21] Computer Generated Native Distribution Map of Globicephala melas (reviewed). www.aquamaps.org, version of Aug. 2010. Web. Accessed 14 Aug. 2012. Expert remarks: Relatively good match with known range extents and sightings, although there is a lot of confusion about these due to sympatric occurrence with short-finned killer whales in some areas and the difficulties to distinguish both species at sea. Some adjustments of temperature envelope (PrefMin & Max thresholds) to more adequately capture temperate occurrence of species. Northern range extent in Atlantic might be too far north. Kristin Kaschner, 2009-09-04.

Table 4-11 Parameters of vocalisations of long-finned pilot whales

Signal type	Frequency range (Hz)	Frequency near Maximum Energy (Hz)	Dominant frequencies (Hz)	Source level (dB re 1 µPa at 1 m)	References
whistles	1,000-8,000		1,600-6,700		Busnel and Dziedzik (1966)
	1,000-8,000	1,600-6,700		178	Wartzok and Ketten (1999)
clicks	1,000-18,000				Taruski (1979) Steiner (1981)
	200-100,000			180	Taruski (1979)

4.2.5 Sperm Whale

Order Cetacea

Suborder Odontoceti

Family Physeteridae

Species *Physeter macrocephalus* (or *catodon)*

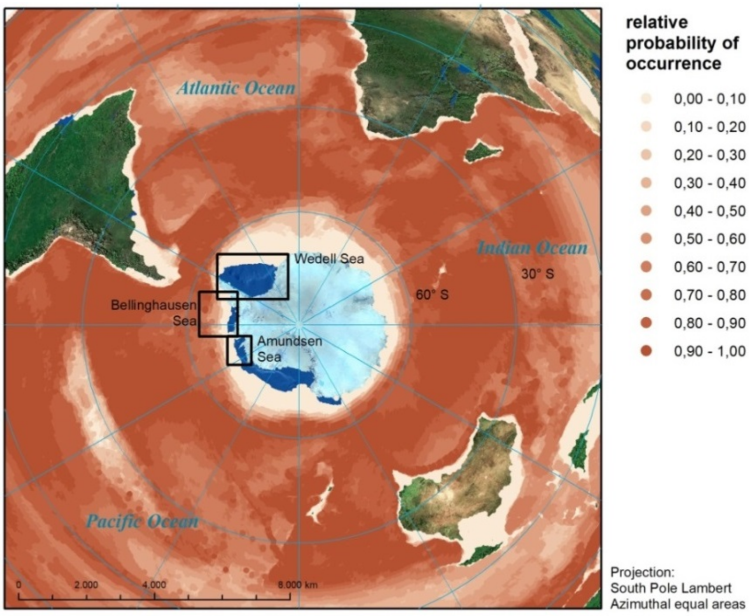
Sperm whales account for some extremes of mammalian species. They are the largest odontocete species with probably the most distinctive sexual dimorphism and the largest brains for this group (Whitehead 2009). They dive very deep (~400-1200 m reaching maximas of >2000 m) and long (~15 min – 1h 13 min) (Amano and Yoshioka, 2003; Aoki et al. 2007; Davis et al. 2007; Thode 2004; Watkins et al. 1993) and have large ranges (Hastie et al. 2003; Jaquet and Whitehead 1999; Jaquet et al. 2003) while living in complex social groups (Coakes and Whitehead 2004; Drouot et al. 2004; Jaquet and Gendron 2009). Furthermore they are one of the loudest animals in the sea and exhibit the largest nose (Cranford 1999; Madsen et al. 2005; Møhl 2001).

Sperm whales were heavily hunted in the 19th and even more in the 20th century (Whitehead 2009). Pre-whaling estimates were calculated to be around 1,100,000 individuals (95 % CI: 672,000 to 1,512,000), while the population at the century turn was probably around 360,000 individuals (Whitehead 2002).

Distribution of sperm whales is mostly determined by deep water depths, but older whaling 'grounds' are considered to be in regions of high primary production (Jaquet, 1996). While females seem to stay in an area of about 1,000 km^2 in a 10 year period, males move much further, even between ocean basins, providing reasoning, why genetic stock structure is generally uniform on a global scale (Dufault et al. 1999)

Kasamatsu and Joyce (1995) reported highest densities for mature males in two areas close off the coast of the Amery shelf-ice and around Wilkesland. The habitat suitability modelling shows higher suitabilities around the Antarctic Peninsula, but is generally low for the Weddell Sea and Amundsen Sea (Fig. 4-29).

Fig. 4-29 Native Distribution map of sperm whales in the Southern Ocean[22], only areas in brown to white shades are modelled outcome, blue areas are not included in the model.



Females primarily prey on squid, but also feed on different fish species. Males tend to take larger food items and are more adapted to demersal fish (Whitehead 2009). Sperm whales produce clicks and creaks for echolocation (Miller et al. 2004b; Møhl et al. 2003; Watwood et al. 2006) and social interactions (Frantzis and Alexiadou 2008; Madsen et al. 2002a; Marcoux et al. 2006; Rendell 2004; Rendell et al. 2012; Watkins and Schevill 1977; Weilgart and Whitehead 1997). Sperm Whales are listed in the IUCN Red List as “Vulnerable A1 (d)” (Taylor 2008g).

Table 4-12 Parameters of vocalisations of sperm whales

Signal type	Frequency range (Hz)	Frequency near Maximum Energy (Hz)	Dominant frequencies (Hz)	Source level (dB re 1 µPa at 1 m)	References
clicks	100-30,000	2,000-4,000 10,000-16,000	2,000-4,000^a 10,000-16,000	160-180 220	Backus and Schevill (1966); Levenson (1974) Watkins (1980) Madsen et al. (2002b) Thode et al. (2002) Mohl et al. (2000)
clicks in coda	16,000-30,000	7,000-9,000		165 peak-peak	Wartzok and Ketten(1999); Madsen et al. (2002b)
pulses				up to 162	Madsen et al. (2006)

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[22] Computer Generated Native Distribution Map of Physeter macrocephalus (reviewed). www.aquamaps.org, version of Aug. 2010. Web. Accessed 14 Aug. 2012. Expert remarks: Good fit with known species´ occurence. Predicted distribution includes northern and southern known maximum range extents of migration of large males. Females and immatures mostly remain below about 40°N and above 40°S. Predictions have been successfully validated in some areas using independent sighting data (Kaschner et al. 2006). Minor modification of salinity cut-off to capture the species´ regular occurence in the Mediterranean. Occurence in the Red Sea is not supported by published data. 2009-09-07, Kristin Kaschner.

Signal type	Frequency range (Hz)	Frequency near Maximum Energy (Hz)	Dominant frequencies (Hz)	Source level (dB re 1 µPa at 1 m)	References
trumpets	500-15,000	500; 3,000		172 peak-peak	Teloni and Zimmer (2005)

4.3 Pinnipeds

Of the six Antarctic seal species one belongs to the family Otariidae or eared seals (Antarctic fur seal) and five to the family Phocidae or earless seals (southern elephant, crabeater, leopard, Ross and Weddell seal)(Boyd, 2009a). Unlike most of the cetacean species, Antarctic seals depend on the Southern Ocean and Antarctica as their primary habitat (Boyd 2009a).

Antarctic seals are either separated in distribution or by their preferred food items (King 1983) but also by their association with fast and pack ice and open water habitats (Boyd 2009a). Antarctic fur seals and elephant seals can be regarded as open water species with Antarctic fur seals staying mostly north and around the Antarctic polar front (Bonner 1981; Forcada and Staniland 2009) while elephant seals range from north of the Antarctic convergence to the pack-ice zone (Hindell and Perrin 2009; Lewis et al. 2006; Ling and Bryden 1981). Crabeater seals roam the pack-ice zone with individuals possibly travelling the whole Antarctic pack-ice zone (Boyd 2009a). Ross seals may range intermediate between pack-ice and open water depending on season (Boyd, 2009a; Ray 1981; Thomas and Rogers 2009a). Leopard seals are year round distributed throughout the pack-ice between the Antarctic convergence and the continent (Kooyman 1981a). Weddell seals are mostly associated with fast ice and the subantarctic islands, but mainly stay south of the Antarctic convergence (Kooyman 1981b).

Weddell, Ross, leopard and crabeater seals are ice breeders, while elephant and fur seals breed onshore. Most seals adapted to the ice show contrasting or disruptive color patterns (Berta 2009). Antarctic seals feed on fish and squid, but crabeater seals show adaptation of the tooth structure to primarily feed on krill. Due to the association patterns between seals and ice it is probable that climate change may have an effect on those species (e.g. Southwell et al. 2008a)

The abundance of seals is mainly given by haulout counts, usually either done during the breeding season or during the moulting season. Aerial surveys with helicopters or fixed wing aircrafts have been undertaken by the Antarctic Pack Ice Seal (APIS) programme to gain a better understanding on seals living in the Antarctic. The multinational and multidisciplinary approach is led by the SCAR (Scientific Committee on Antarctic Research) – Expert Group on Seals. First results and reports of abundance for smaller areas are available from their website[23].

Life history of seals has not yet been fully assessed for the Antarctic seal species, but some, like for instance Weddell seals have been researched primarily by mark-recapture studies (Boyd 2009b). Some parameters for better known species are given in Table 4-13.

For seals one major aspect with regard to masking studies is of course the seasonal cycle of feeding periods alternating with giving birth, nursing, mating and moulting. During breeding and moult animals spend extensive time on their haulout, but are probably more receptive for disturbance due to hormonal changes and changed food consumption. This has to be taken into account especially for the land-breeding southern elephant seals and Antarctic fur seals, which do not exhibit very active communication during the breeding season underwater. Weddell, Ross, crabeater and leopard seal are among the aquatic-breeding pinnipeds, that are vocally more active (Bowen et al. 2009). For Weddell seals it also has to be taken into account that distribution during the breeding season can be clumped around breathing holes in the ice (Bowen et

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[23] http://www.seals.scar.org (accessed 2012/09/04).

al. 2009), and hence noise impacts can possibly affect a larger proportion of individuals simply by chance and location of breathing holes.

To evaluate conservation aspects it is important to know, that Antarctic fur seals were hunted to near-extinction by sealing and whaling activities until 1830 and it was considered to be extinct until 1920. Elephant seals were overexploited in a similar fashion.

Table 4-13 Some measure of life-history for 4 species of Antarctic seals (reproduced from Boyd 2009b).

Species	Mean female body mass (kg)	Mean male body mass (kg)	Pup survival rate	Adult female survival rate	Adult male survival rate	Mean age at first parturition (years)	Mean pregnancy rate	References
Elephant seal	400-500	2100	0,98	0,67-0,88	0,50-0,83	3-4	0,88	McCann(1985); Hindell (1991); Galimberti and Boitani (1999)
Weddell seal	350-425	-	0,80-0,92	0,76-0,85	-	4-5	0,46-0,79	Testa (1987); Testa and Siniff (1987); Testa et al. (1990); Hastings and Testa (1998)
Crabeater seal	220	-	0,21 (Survival in first year)	0,9-0,97	-	2,5	0,95-0,98	Boveng (1993)
Antarctic fur seal	45	188	0,69-0,96	0,83-0,92	0,5	3	0,68-0,77	Wickens and Yorck (1997)

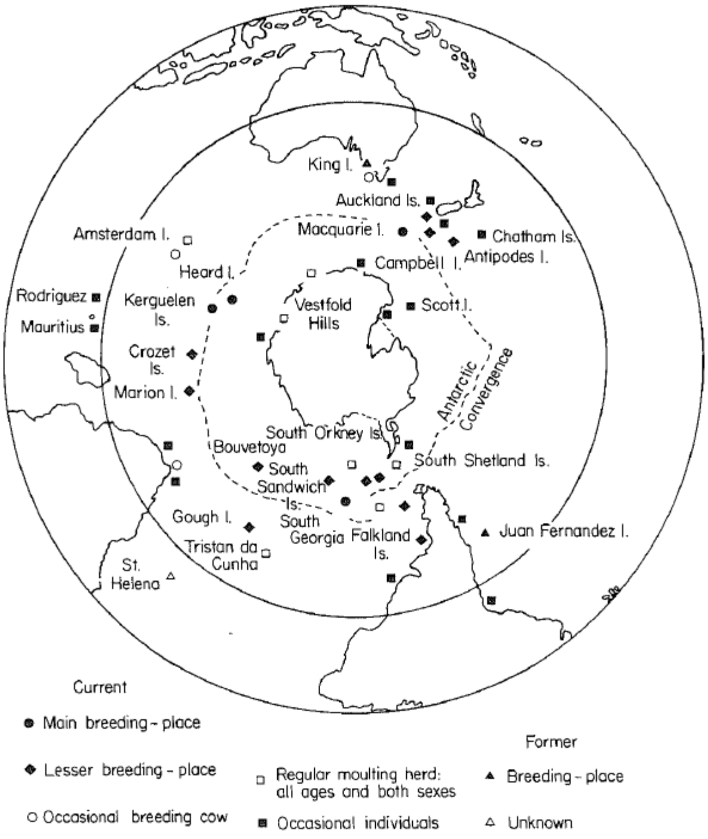
4.3.1 Southern Elephant Seal

Order	Carnivora
Suborder	Pinnipedia
Family	Phocidae
Subfamily	Monachinae
Species	*Mirounga leonina*

Elephant seals have a very strong sexual dimorphism with the male animals being 5-6 times heavier than the females (Boyd 2009a, 2009b). Furthermore males have an elongated proboscis that plays a large role in dominance displays (Hindell and Perrin 2009). Southern elephant seals were hunted especially around South Georgia and Kerguelen where whaling and sealing stopped after 1960 (Ling and Bryden 1981). Main breeding islands are South Georgia, Kerguelen, Heard Island and Marion Island (Ling and Bryden 1981; Fig. 4-30), but breeding has also been reported on the Antarctic Peninsula. Four stocks can be distinguished by genetic structure: the southern Pacific, southern Atlantic and southern Indian Ocean and a smaller population at Peninsula Valdez in Argentina (Hindell and Perrin 2009).

The population in the south Atlantic seems to be stable or increasing (Hindell and Perrin 2009), while large decreases were registered for Macquarie Islands, Heard Island, Kerguelen (females) and Marion Island in the 1980’s (Mccann and Rothery 1988). After a serious decrease from 1952 to 1985, that nearly halved the population, colonies at Macquarie Island seemed to be stabilizing (Hoff et al. 2007). A 66.3 % decline was even calculated for the relatively small population at Prince Edwards Island between 1977 and 2004 (Bester and Hofmeyr 2005). Reasons for declines are not fully understood (Campagna, 2008).

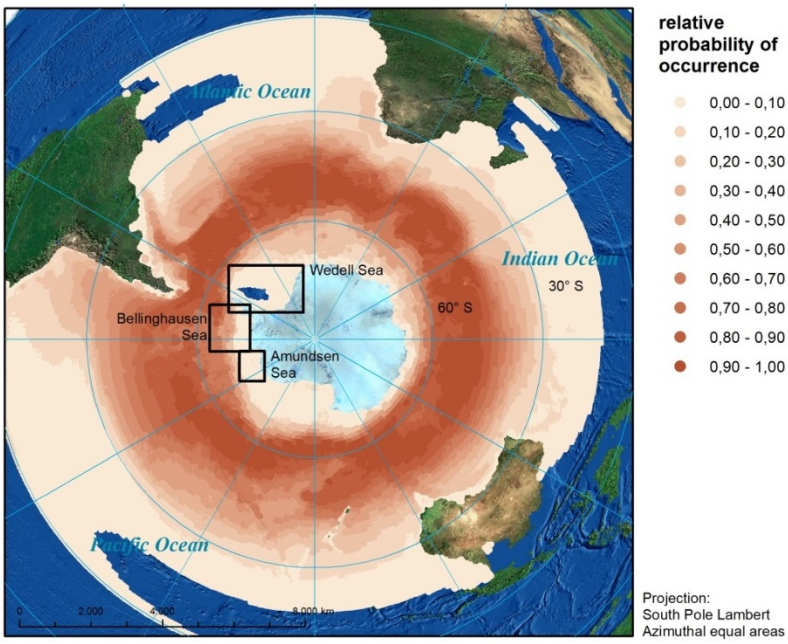
Fig. 4-30 Main breeding islands of southern elephant seals (taken from Carrick and Ingham, 1962 cited in Ling and Bryden, 1981)



Habitat suitability models show a circumpolar distribution with highest suitabilities between 60°S and 45°S (Fig. 4-31) with higher probalities of occurrence around the Bellingshausen Sea and the Antarctic Peninsula. Female southern elephant seals stay closer to the breeding sites, while there is evidence that males use large proportions of the Southern Ocean mostly south (Authier et al. 2012; Bailleul et al. 2007a, 2007b; Bornemann et al. 2000; Tosh et al. 2008) but also north of the Antarctic convergence (Lewis et al. 2006).

In the 1990s the worldwide population of *M. leonina* was estimated at 650,000 animals and major breeding populations seem to be stable or increasing (Campagna 2008). Southern elephant seals are listed in the IUCN Red List as “Least Concern” (Campagna 2008). Nevertheless, the IUCN notes that status for certain populations and breeding sites show a decline and should be treated on a finer spatial/population scale.

Fig. 4-31 Native Distribution map of southern elephant seals in the Southern Ocean[24], only areas in brown to white shades are modelled outcome, blue areas are not included in the model.



Southern elephant seals prey mainly on squid and to a lesser proportion on fish (Carlini et al. 2005; Hindell and Perrin 2009; Hückstädt et al. 2012; Ling and Bryden 1981; McIntyre et al. 2012;

They are very efficient deep divers to a depth of up to 2,000 m (Bailleul et al. 2008; Bennett et al. 2001; Campagna et al. 2007; Hindell et al. 1991). Remote sensing was used on elephant seals to track changes in relative body composition including measurements of buoyancy by drift components of the dive (Thums et al. 2008). This allowed concluding that areas where body lipid increased compared well to areas where seals spent the most time.

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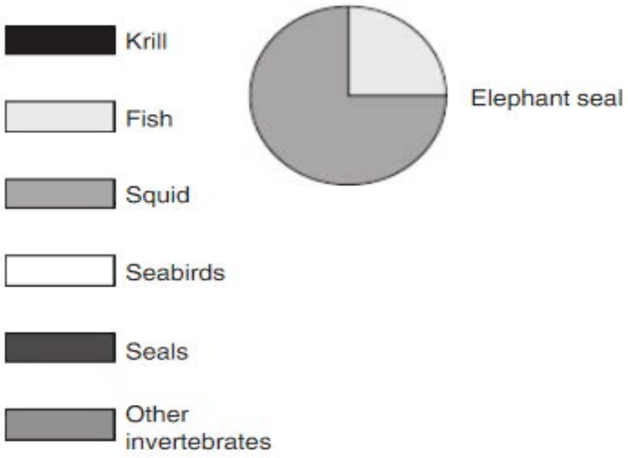
[24] Computer Generated Native Distribution Map of Mirounga leonina (reviewed). www.aquamaps.org, version of Aug. 2010. Web. Accessed 14 Aug. 2012. Expert remarks: Relatively good match with known distribution of species, although its occurrence along the coast of Antarctica is not captured well. Northern low probability predictions include many but not all of the known vagrant records for the species. Adjustment of temperature and sea ice envelope necessary to reflect this species concentration in subpolar and polar waters. Predictions would be improved by the incorporation of seasonality. 2010-03-09, Kristin Kaschner.

Fig. 4-32 Composition of the diet of southern elephant seals (taken from Boyd 2009a)



Killer whales are known to attack elephant seals, but leopard seals and large sharks also prey on southern elephant seals.

Elephant seals use vocalisations mainly in-air. Knowledge about underwater vocalisations has not yet been collected in detail.

Table 4-14 Parameters of in-air vocalisations of southern elephant seals

Signal type	Frequency range (Hz)	Frequency near Maximum Energy (Hz)	Dominant frequencies (Hz)	Source level (dB re 1 µPa at 1 m)	References
Male in-air call	178-1,617[1]				Sanvito and Galimberti (2000a, 2000b); Sanvito et al. (2007a, 2007b)
Female pup attraction call	50-3,000[1]				

4.3.2 Antarctic Fur Seal

Order Carnivora

Suborder Pinnipedia

Family Otariidae

Subfamily Arctocephalinae

Species *Arctocephalus gazella*

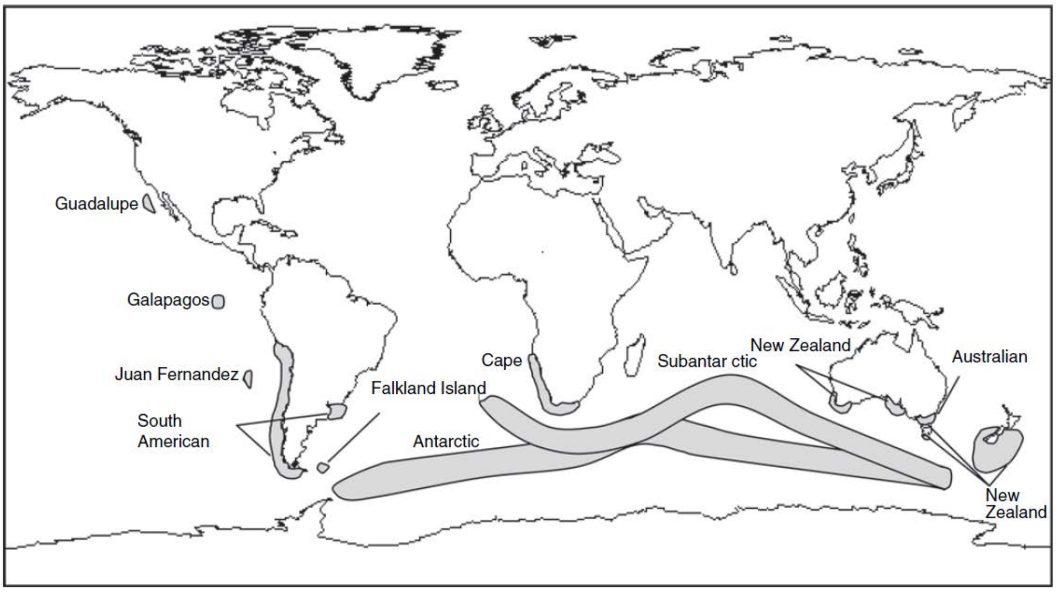
Arctocephalus gazella is one of eight species of southern fur seals (Thomas and Rogers 2009b). During sealing times, fur seals were hunted so intensively, that some of those eight species were regarded as extinct, including *A. gazella* (Arnould 2009). Antarctic fur seals overlap largely in distribution with subantarctic fur seals (*Arcotcephalus tropicalis*, Arnould 2009; Luque et al. 2008). Close to the Antarctic Peninsula the subspecies of *A. australis glacilis* on the west coast of South America and *A.a. australis* on the Falkland Islands should be considered as well. The

Falkland Island subspecies still suffers from sealing and have not reached presealing population size. Nevertheless the Antarctic fur seal has the farthest reach south towards Antarctica and is common around the Peninsula. Otherwise *A. gazella* is very common and occurs mostly north off and around the Antarctic Convergence (Boyd 2009a).

Little information exists about their migration patterns. However, it is known that about 95% of all Antarctic fur seals can be found at the island of South Georgia and most of them breed there (Aurioles and Trillmich 2008, Fig. 4-34). During the mating and breeding season, Antarctic fur seals live together in colonies. They can also begat hybrids with other fur seals, for example with the subantarctic fur seal (Aurioles and Trillmich 2008).

The bulls arrive at the breeding grounds a few weeks earlier (early November) than the cows. It was observed that bulls travel long distances between the breeding grounds to the ice edge after the mating season. The females stay with the pups for nursing until April. In austral winter, bulls and juveniles mostly occur near their breeding grounds while the females travel to the ice edge or out of to the polar front (Forcada and Staniland 2009).

Fig. 4-33 Distribution of southern fur seals with regard to species and subspecies level (Arnould 2009)



Generally, Antarctic fur seals prey on krill, but the nutrition depends on season and location. In some areas (Heard Island, Macquarie Island) krill is not available and the seals prey also on cephalopods, fish and even penguins (Fig. 4-36, Bailleul et al. 2005; Casaux et al. 2003; Ciaputa and Siciński 2006; Croxall et al. 1985; Daneri et al. 2005, 2008; Luque et al. 2007; Makhado et al. 2007). Antarctic fur seals mostly dive for foraging at night. Generally, their dives are short and not very deep (0-40m) (Aurioles and Trillmich 2008; Forcada and Staniland 2009; Boveng et al. 1996; Boyd et al. 1995; Croxall et al. 1985).

Fig. 4-34 Antarctic fur seal breeding distribution and pup production (Forcada & Staniland 2009).

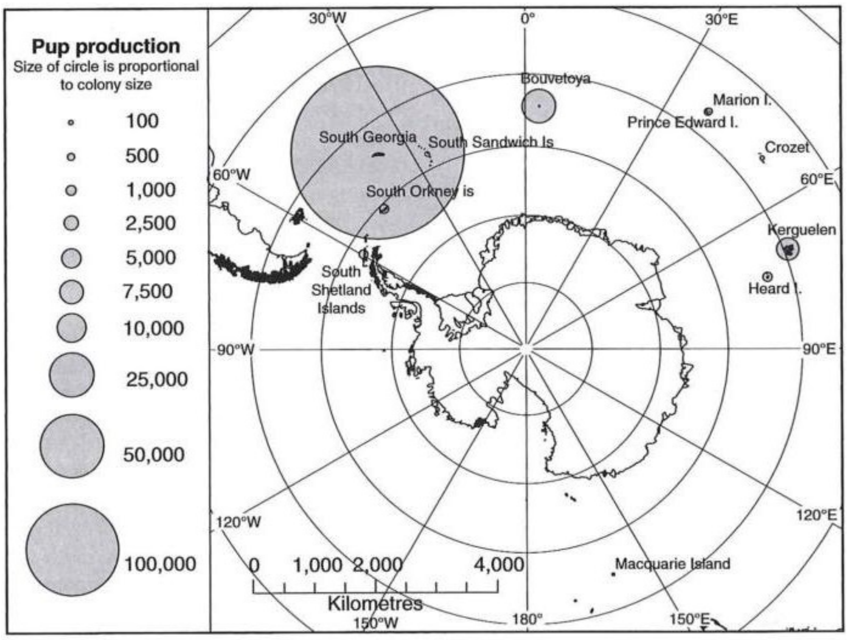
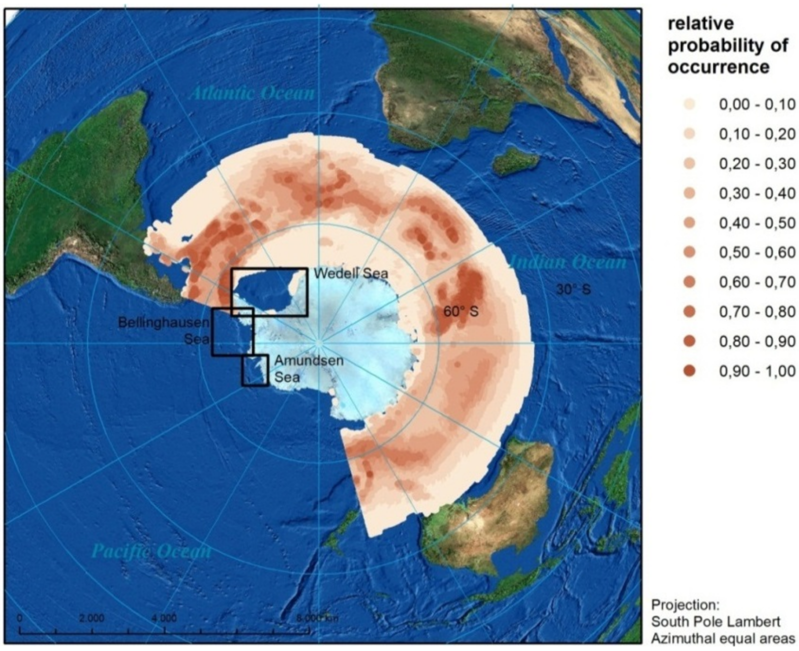


Fig. 4-35 Native distribution map of Antarctic fur seal [25] in the Southern Ocean, only areas in brown to white shades are modelled outcome, blue areas are not included in the model.



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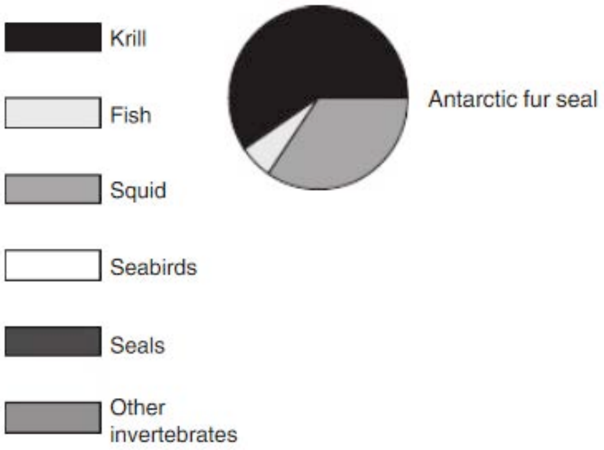
[25] Computer Generated Native Distribution Map of *Arctocephalus gazella* (reviewed). www.aquamaps.org, version of Aug. 2010. Web. Accessed 22 Aug. 2012. Expert remarks: Not a great match with known distributional ranges, but this is mostly due to the difficulties to reconcile available point data with published range map (e.g. compare available OBIS data with IUCN range map for species). Temperature envelope had to be adjusted substantially downwards, since default settings were driven by records from around the coast of Australia where species is supposed to occur only as vagrant. Some adjustment of ice envelope to reflect polar distribution and some minor adjustment of primary production envelope to eliminate "holes" in predictions. Kristin Kaschner, 2010-03-08.

Fig. 4-36 Composition of the diet of Antarctic fur seals (taken from Boyd 2009a)



The population size is estimated in the range of 4.5-7 million individuals and at large the population size seems to increase (Aurioles and Trillmich 2008).

Antarctic fur seals have only few natural enemies. However, killer whales as well as leopard seals are dangerous for young animals (Forcada and Staniland 2009).

Antarctic fur seals are listed in the IUCN Red List as “Least Concern” (Aurioles and Trillmich 2008).

The sounds of the Antarctic fur seals depend on gender and social circumstances (Table 4-15). If they feel threatened or are aggressive, the males produce a threatening roar (full-threat call). However, if they want to interact with other individuals or are moving around a territory, they produce a “huff-chuff” sound. The females and their pups have also developed special sounds to recognize each other (Forcada and Staniland 2009).

Table 4-15 Parameters of vocalisations of fur seals

Signal type	Frequency range (Hz)	Frequency near Maximum Energy (Hz)	Dominant frequencies (Hz)	Source level (dB re 1 µPa at 1 m)	References
Bark	100-8,000	713			Page et al. (2002)
Full threat call (female pup attraction call has similar acoustic features as FTCs)	100-3,000	773			Page et al. (2002)

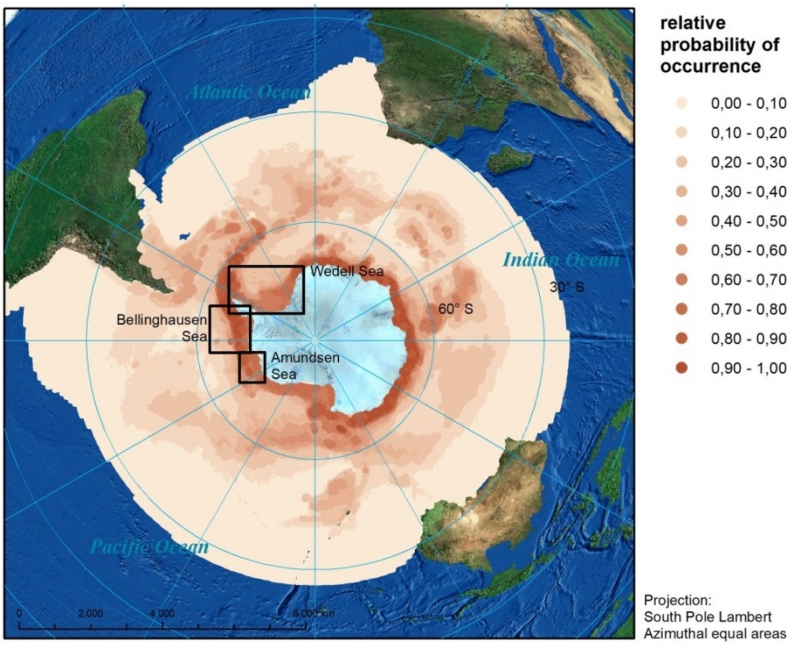
4.3.4 Crabeater Seal

Order	Carnivora
Suborder	Pinnipedia
Family	Phocidae
Subfamily	Monachinae
Species	*Lobodon carcinophaga*

Crabeater seals are probably the most abundant seal species in the world (Bengtson 2009). They show a panmictic circumpolar distribution, are strongly associated with pack-ice in its seasonally varying magnitude and are occasionally found in higher latitude (Bengtson 2009; Kooyman 1981c, Fig. 4-37). Higher densities of crabeater seals are often found near the continental shelf and in the marginal ice zone (Burns et al. 2004; Southwell et al. 2005).

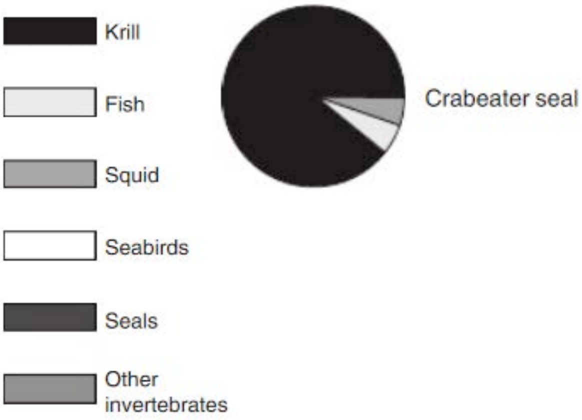
Antarctic krill (*Euphausia superba)* is the main prey for crabeater seals throughout the year and comprises over 95% of the crabeater seal diet. During foraging the seals dive for periods of up to 16 hours (Bengtson 2009). They can dive to 528 m and most feeding dives last 20-30 minutes and shorter in duration (Bengtson and Stewart 1992; Burns et al. 2008; Nordøy et al. 1995). Crabeater seals adapt their feeding dives to the daily vertical migration of krill and therefore dives at dawn are deeper than at night (Southwell 2008a).

Fig. 4-37 Native distribution of crabeater seals in the Southern Ocean[26], only areas in brown to white shades are modelled outcome, blue areas are not included in the model.



In the water crabeater seals can form large groups of up to 200 seals, breathing and diving synchronously (Gales et al. 2004; Wall et al. 2007). On their haul-out on ice floes they are nevertheless often seen in groups of only one or two animals. It has been hypothesized that crabeater seals use the large groups in synchronous fashion as a coordinated feeding strategy (Gales et al. 2004). How communication and coordination is controlled during these events is unclear, but vocal communication is from our perspective probable. During the breeding season until the end of lactation, a female, her pup and an attendant male stay together as a group (Bengtson 2009; Southwell 2008a).

Fig. 4-38 Composition of the diet of Crabeater seals (Boyd, 2009a)



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[26] Computer Generated Native Distribution Map of Lobodon carcinophaga (reviewed). www.aquamaps.org, version of Aug. 2010. Web. Accessed 14 Aug. 2012. Expert remarks: Predictions correspond well with known distributions including low probability areas representing areas where the species is mostly known from vagrant records. Species is closely associated with sea ice and therefore seasonal changes in distribution can be expected to be quite large. Would be improved by use of seasonal predictions. 2010-03-08, Kristin Kaschner

The population size is estimated in the range of 7-12 million individuals and there is no available trend in the abundance (Southwell et al. 2008a). Aerial surveys (in 1999/2000) between 64 and 150°E found an abundance of 950,000 individuals (95 % CI 700,000-1,400,000) in that part of Antarctica (Southwell et al. 2008a). The large confidence limits indicate that monitoring of the species population will be difficult due to uncertainty. Crabeater seals are listed in the IUCN Red List as "Least Concern" (Southwell 2008a). Crabeater seals often show scars, most probably from attacks by leopard seals (Bengtson 2009).

Table 4-16 Parameters of vocalisations of crabeater seals

Signal type	Frequency range (Hz)	Frequency near Maximum Energy (Hz)	Dominant frequencies (Hz)	Source level (dB re 1 µPa at 1 m)	References
groan	<100-8,000+		100-1,500	high	Stirling and Siniff (1979)
low moan call	250-2,600	612			"
high moan call	990-4,900	1,308			Klinck et al. 2010

4.3.5 Leopard Seal

Order Carnivora

Suborder Pinnipedia

Family Phocidae

Subfamily Monachinae

Species *Hydrurga leptonyx*

Leopard seals are mainly found around the Antarctic pack ice (Rogers 2009) where they spend most of their time. Breeding grounds are also found on pack ice where the density of seals is highest in areas with low amounts of pack-ice available as haul-outs (Rogers 2009). However, high accumulations are also found around Heard Island and South Georgia (Kooyman 1981a) and habitat suitability modelling (Fig. 4-39) suggest higher densities around the Antarctic Peninsula as well.

On haul-outs leopard seals show diurnal variation in haul-out behaviour, spending more time during the day in water from June to September (Kooyman 1981a). This has been reported for Heard Island and similar patterns were also seen in Weddell seals in McMurdo Sound (Kooyman 1981a). Movements depend on the seasonal change of ice extent and migration pattern of prey (Forcada and Robinson 2006). Leopard seals are mostly solitary animals, even during the breeding season (Nordoy and Blix 2009). Studies using photo-identification and tagging on South Georgia resulted in the hypothesis that older animals showed long-term site fidelity while younger animals may be more dispersed and are attracted by prey abundance (Forcada and Robinson 2006).

It was observed, that their dives are short and not very deep – usually not longer than 5 minutes and not deeper than 52 m. However, leopards seals can dive 300 m deep and can stay under water for 15 minutes (Nordoy and Blix 2009).

Fig. 4-39 Native Distribution map of leopard seals in the Southern Ocean[27], only areas in brown to white shades are modelled outcome, blue areas are not included in the model.

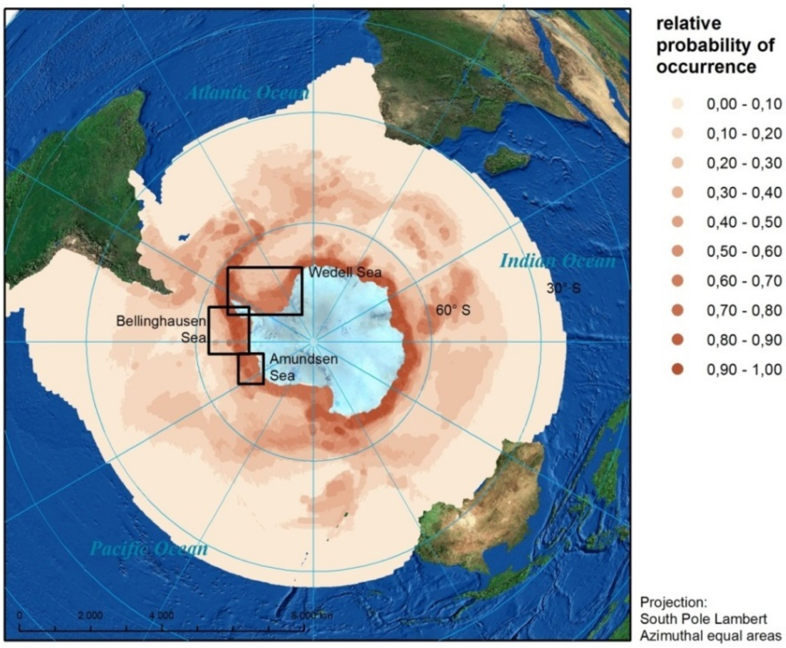

Fig. 4-40 Diet composition of leopard seals (Boyd 2009a)

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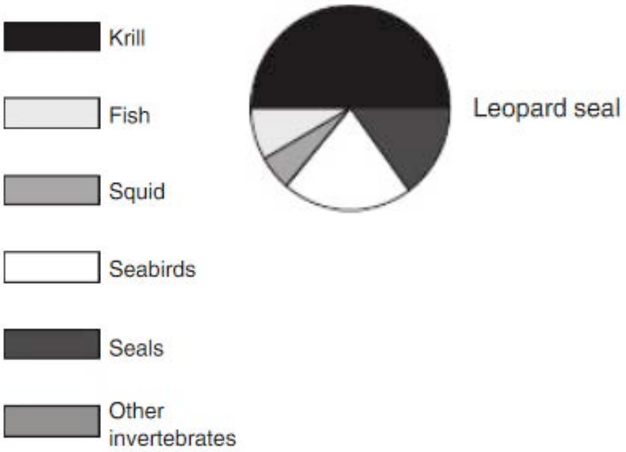
[27] Computer Generated Native Distribution Map of Hydrurga leptonyx (reviewed). www.aquamaps.org, version of Aug. 2010. Web. Accessed 14 Aug. 2012. Expert remarks: Predictions match known species occurrences, including dispersed winter distribution relatively well, although low probability ranges might extend too far north along southern South America, Africa, Australia and New Zealand. Adjusted temperature and ice envelope during expert review to capture species close association with sea ice areas and the concentration in Antarctic waters. Small modifications of minimum and maximum primary production and salinity envelope settings to eliminate unexplained "holes" in distribution. Kristin Kaschner, 2010-03-08.



Leopard seals feed primarily on krill, especially in the winter months, when other food resources are scarce (Rogers 2009). However, studies using satellite tags seem to question this hypothesis, as seals showed short, shallow dives that did not reach depths preferred by krill (Kuhn et al. 2005). Studies on the Antarctic Peninsula nevertheless show that krill is the most frequent food item followed by penguins and fish (Casaux et al. 2008). Quite often they prey on others seals too (Forcada and Robinson 2006), especially juvenile crabeater seals are a preferred food item (Rogers 2009,

Estimations of population size range from 222,000 to 440,000 individuals. Estimates are very difficult to obtain and they may not represent the population adequately (Southwell et al. 2008b). Leopard seals are listed in the IUCN Red List as “Least Concern” (Southwell 2008b).

They can produce a variety of different call types depending on circumstances. Underwater they use their sounds particularly before and during the breeding season (Rogers et al., 1996). At this time the females produce long-distance acoustic displays (Rogers 2009). From November to January males produce stereotype vocalisations for longer periods (Rogers 2009).

Table 4-17 Parameters of vocalisations of leopard seals

Signal type	Frequency range (Hz)	Frequency near Maximum Energy (Hz)	Dominant frequencies (Hz)	Source level (dB re 1 µPa at 1 m)	References
pulses (trills)	100-5,900				Ray (1970); Stirling & Siniff (1979); Rogers et al. (1995)
thump, blast, roar, etc.	40-7,000				Rogers et al. (1995)
ultrasonic	up to 164		50-60	low	Thomas et al. (1983a)
ascending trill	200-800				Klinck (2008)
descending trill	300-700				Rogers et al. (1995)
high double trill	2,600-3,500				Rogers et al. (1995); Klinck (2008)
hoot	130-320				Rogers et al. (1995)
hoot single	150-300				“

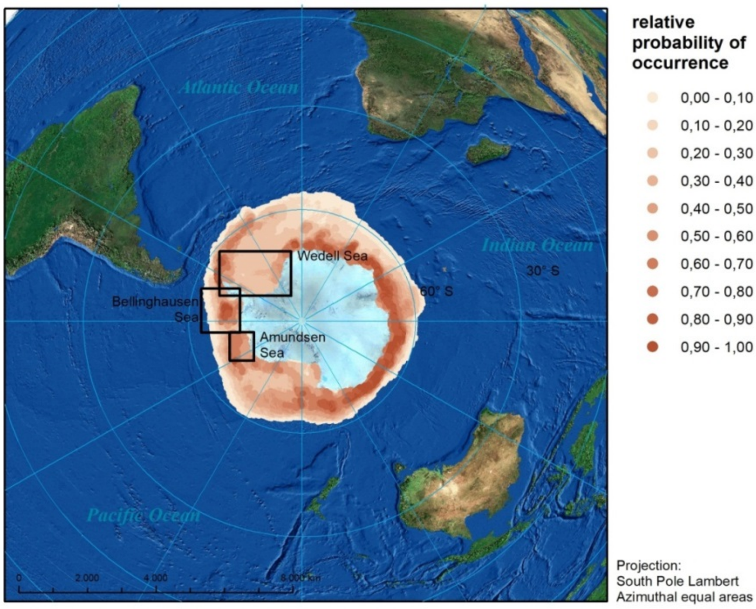
trill					
low double trill	200-400				“
mid single trill	1,500-2,100				“
thump pulse	40-180				“
nose blast	1,800-2,700				“
roar	130-4,500				“
Blast	80-6,100				“
growl	35-200				“
snort	100-230				“

4.3.6 Ross Seal

Order	Carnivora
Suborder	Pinnipedia
Family	Phodidae
Subfamily	Monachinae
Species	*Ommatophoca rossii*

Ross seals show a circumpolar distribution with highest habitat suitability around the Ross shelf ice and especially for the eastern parts of Antarctica (Fig. 4-41). They stay within the pack ice for breeding, moulting and resting (Southwell 2008c). Ross seals are probably the least abundant Antarctic seal species, or the one most difficult to estimate abundance for (Southwell et al. 2008c) and may be still the one least known (Ray 1981).

Fig. 4-41 Native Distribution map of Ross sealsin the Southern Ocean[28], only areas in brown to white shades are modelled outcome, blue areas are not included in the model.



The breeding period begins in November and the pups are nursed for about a month. The moulting phase takes place from mid-January to mid-February (Ray 1981; Thomas and Rogers 2009a). There is little information about the migration patterns of Ross seals but it has been observed that they can travel as far north as up to 50°S after moulting (Blix and Nordoy 2007). Habitat suitability modelling shows high suitability for the Bellingshausen Sea and around the northern tip of the Antarctic Peninsula (Fig. 4-41).

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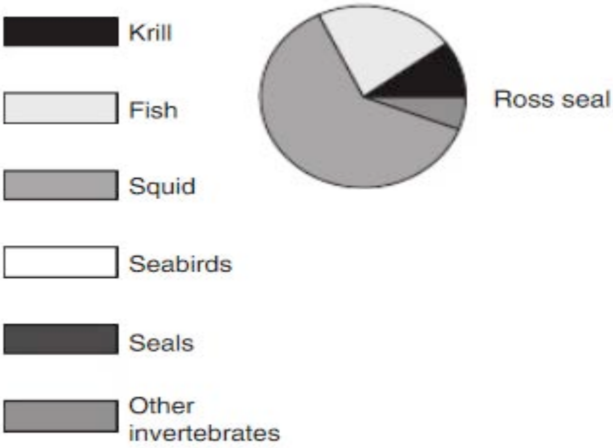
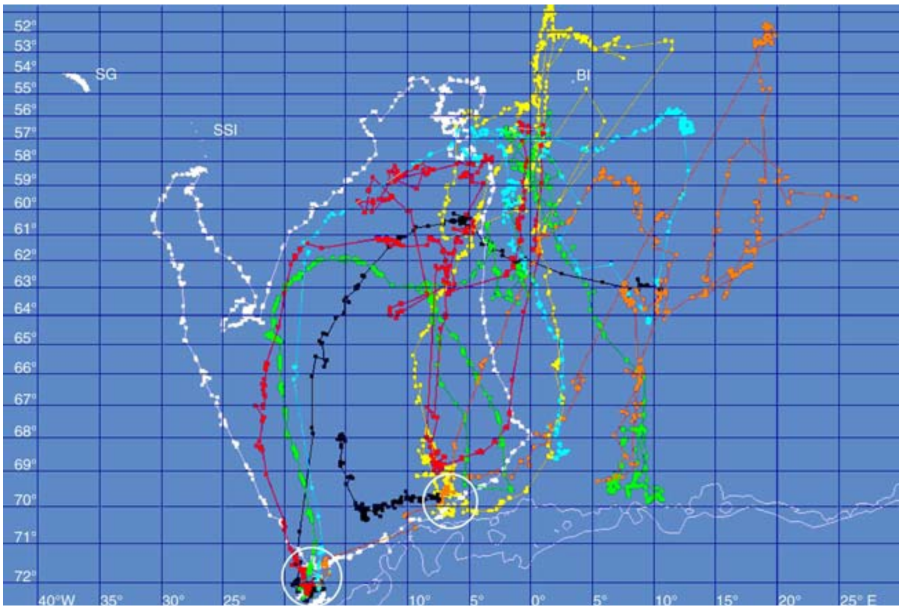
[28] Computer Generated Native Distribution Map of *Ommatophoca rossii* (reviewed). www.aquamaps.org, version of Aug. 2010. Web. Accessed 22 Aug. 2012. Expert remarks: Good match with known distribution of species, although there is only very limited information at the moment. Adjustment of maximum temperature and ice concentration settings to reflect known habitat usage and very polar distribution. Minor adjustments of salinity & primary production envelopes to eliminate unexplained "holes" in distribution. Predictions do not capture vagrants to S Australia, Kerguelen and Heard Island. Would be improved by use of seasonal prediction. Kristin Kaschner, 2010-03-17.

Fig. 4-42 Composition Ross seal diet (from Boyd, 2009a



The population size is estimated to be around 130,000 individuals and there is no known trend in abundance (Southwell 2008c). Due to their haul-out behaviour in dense pack ice, icebreakers and long range aircraft are necessary for abundance estimates. For East Antarctica shipboard and aerial surveys have been conducted between 64°E to 150°E resulting in an estimate of 41,300 to 55,900 Ross seals (Southwell et al. 2008c). 95 % confidence limits ranged from 20,500 to 226,600 animals showing the extreme uncertainty in these estimates. Generally, Ross seals are solitary animals (Thomas and Rogers 2009a).

Fig. 4-43 Overall movements of nine adult Ross seals, tagged with SDRs in mid-February 2001 (from Blix & Nordoy 2007).



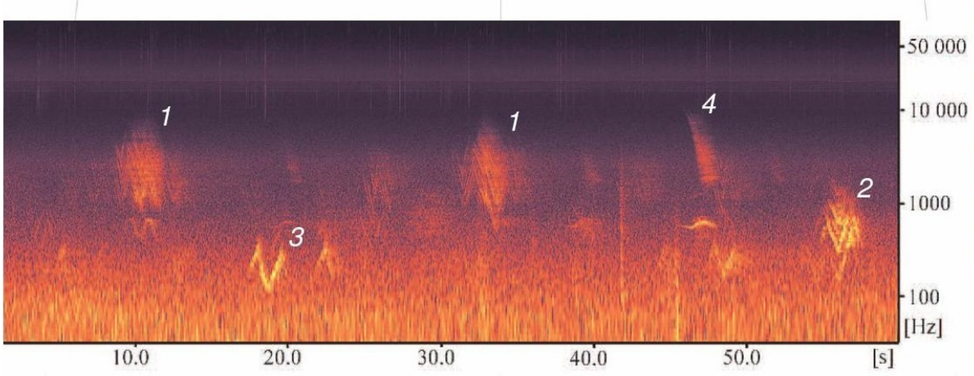
The diving behaviour of Ross seals varies diurnally, probably according to the depth distribution of their preferred prey or as a predator avoidance reaction (Bengtson and Stewart 1997). Ross seals prey on cephalopods but quite often they feed on krill and mid-water fish, too (Thomas and Rogers 2009a, Fig. 4-42). Predators feeding on Ross seals are killer whales and leopard seals (Southwell 2008c).

During the time they spend off shore, usual dives last up to 15 min. When they are near the ice edge Ross seals dive for shorter time periods of 5-10 minutes. They can dive up to 400 meters deep but mostly stay in the 52-100 m depths range, while travelling long distances within the pack-ice (Blix and Nordoy 2007, Southwell 2005, Fig. 4-43).

Ross seals are listed in the IUCN Red List as “Least Concern” (Southwell 2008c).

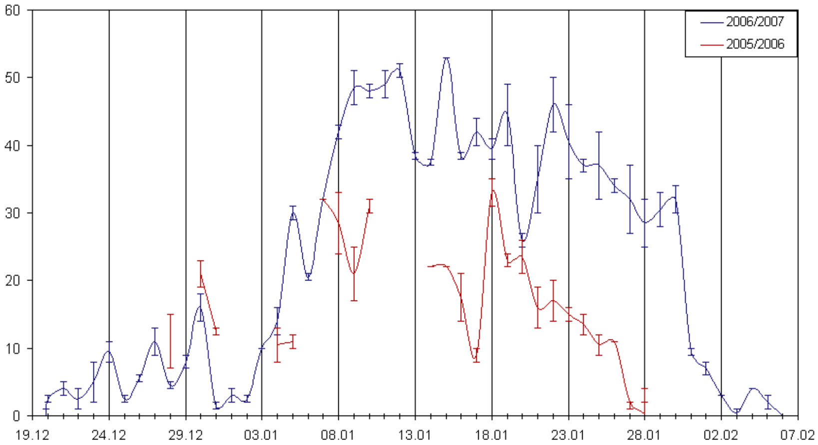
In water Ross seals use their calls particularly between December and February, matching the breeding season (Oopzeland et al. 2010). Seibert et al. (2007) identified four different call types (Fig. 4-44). Calling patterns varied with season (Fig. 4-45) and had diurnal components (Seibert et al. 2007). Parameters of vocalisations can be found in Table 4-18.

Fig. 4-44 Spectrogram of a Ross seal recording



Four Ross seal call types were identified: high siren call (1), mid siren call (2), low siren call (3), & the whoosh (4) (reproduced from Seibert et al. 2007).

Fig. 4-45 Number of Ross seals calls per minute



Number of calls per minute (y-axis) over the whole period (x-axis) when Ross seals vocalise in the vicinity of PALAOA recordings (red line in 2005/6, blue in 2006/7). The seals arrive in mid-December and leave the area in the beginning of February (reproduced from Seibert et al. 2007).

Table 4-18 Parameters of vocalisations of Ross seals

Signal type	Frequency range (Hz)	Frequency near Maximum Energy (Hz)	Dominant frequencies (Hz)	Source level (dB re 1 µPa at 1 m)	References
pulses	250-1,000				Watkins & Ray (1985)

siren	4,000 -> 1,000 -> 4,000				“
high sirene call	800-4,30	1,590			Seibert et al. (2007)
mid sirene call	340-930	500			“
low sirene call	140-370	230			“
start-up sound	540-690	610			“
whoosh	1,400-6,700	2,300			“

4.3.7 Weddell Seal

Order	Carnivora
Suborder	Pinnipedia
Family	Phocidae
Subfamily	Monachinae
Species	*Leptonychotes weddellii*

The Weddell seal is a widely distributed seal species and occurs circumpolar around Antarctica, preferring fast-ice (Fig. 4-46), but is occasionally also seen on the sub-Antarctic Islands. The population size is estimated at a minimum of 500,000 individuals and there is currently no known trend in the abundance (Gelatt and Southwell 2008). Weddell seals breed on ice from late September until the beginning of November. During this time the seals form colonies of up to 50 females with pups (Thomas and Terhune 2009).

Weddell seal males have strategies to find holes (Wartzok et al. 1992) and maintain their -hole year round by raking on the edges of the hole with their teeth (Thomas and Terhune 2009). Weddell seals are extremely good divers reaching depths of about 600 meters and can stay under the surface for about 82 minutes (Davis et al. 2003; Harcourt and Hindell 2000; Schreer and Testa 1996).

Weddell seals primarily prey on fish, for example the Antarctic cod (Thomas and Terhune 2009) and Antarctic silverfish (Davis et al. 2013). Killer whales take Weddell seals of all sizes, but leopard seals probably do not feed on Weddell seals (Kooyman 1981b; Thomas and Terhune 2009). It was observed, that they stop calling when killer whales and leopard seals arrive in their areas (Thomas and Kuechle 1982).

Weddell seals are listed in the IUCN Red List as “Least Concern” (Gelatt & Southwell 2008).

Fig. 4-46 Native Distribution map of Weddell seals in the Southern Ocean[29], only areas in brown to white shades are modelled outcome, blue areas are not included in the model.

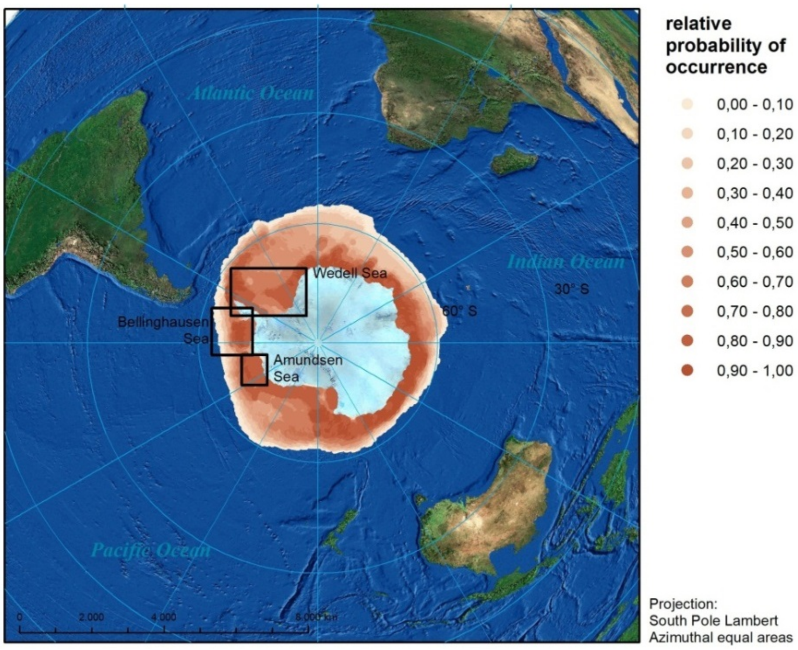


Fig. 4-47 Composition of Weddell seal diet (Boyd, 2009a)

There was an attempt to measure the hearing abilities of a Weddell seal using audio evoked potentials, but unfortunately it failed (Thomas and Terhune 2009). Weddell seals produce a variety of different call types (Kooyman 1981b; Thomas and Terhune 2009). They vary seasonally and diurnally and are depending on social circumstances (Green and Burton 1988). Males for example use loud trills to mark their territory. Females and their pups have also developed special sounds to recognise each other (Thomas and Terhune 2009). A great deal of research has already been carried out to classify vocalisations (Table 4-19) of air-born mother-pup communication (Collins

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[29] Computer Generated Native Distribution Map of Leptonychotes weddellii (reviewed). www.aquamaps.org, version of Aug. 2010. Web. Accessed 22 Aug. 2012. Expert remarks: Very limited information about species distribution, but predictions match known occurrence relatively well. However, they do not capture vagrants along S America, S Australia, New Zealand and Juan Fernandez Islands. Given close association with sea ice, predictions would probably be improved by incorporation of seasonal changes. Minor adjustment of minimum and maximum primary production and salinity envelope settings to eliminate unexplained "holes" in predicted distribution. Kristin Kaschner, 2010-03-08.

and Terhune 2007; Collins et al. 2005, 2006), annual and diurnal variation in underwater vocalisations (Green.and Burton 1988), repetitive patterns (Moors and Terhune 2004), seasonal variation (Rouget et al. 2007) and geographic variation (Terhune et al. 2008). Furthermore playback experiments were carried out (Thomas et al. 1983b).

Table 4-19 Parameters of vocalisations of Weddell seals

Signal type	Frequency range (Hz)	Source level (dB re 1 µPa at 1 m)	References
34+ call types	100-12,800	153-193	Thomas and Kuechel (1982); Thomas et al. (1983b); Thomas and Stirling (1983)
trill (T), DT223,DT212, DT215, DTC225, CT, W1	100-15,000		Schevill and Watkins (1965); Kooyman (1968); Pahl et al. (1997); Terhune and Dell'Apa (2006)
cricket call (R),DTC205, DL218,LR, HR, MR, W13	700-6,000		Thomas (1979); Pahl et al. (1997); Terhune and Dell'Apa (2006)
gutteral glug (G)	100-1,000		Thomas (1979); Terhune and Dell'Apa (2006)
mew (M), DM220	500-2,000		Poulter (1968); Pahl et al. (1997)
eeyoo (E),DWD201	100-8,000		Kooyman (1968); Kaufmann et al. (1975); Pahl et al. (1997)
growl (L)	100-1,000		Thomas (1979)
chirp (P), W5	200-3,000		Schevill and Watkins (1965)
chug (C), DC228,DC222, low single chirp (W6), sequence (W7)	50-1,000		Ray and Schevill (1967); [Terhune and Dell'Apa (2006); Pahl et al. (1997)
click (A)	100-4,000		Thomas (1979)
seitz (Z), pulse sequence (W14)	100-3,000		Thomas (1979);
knock (K)	100-1,000		Thomas (1979)
teeth chatter (H)	1,000-8,000		Kaufmann et al. (1975)
DWA207, DS213,rising tone (W11)	500-8,000		Pahl et al. (1997
DG230,DWAG241, oomp (W8)	100-300		"
DT221, falling tone (W9, W10)	200-4,000		"
DC202 (rising chirps)	1,500-4,000		Pahl et al. (1997)
DWA248 (rising whistle)	1,000-5,000		"
DWD210,descending whistle(WD)	8,000-1,000		Pahl et al. (1997); Terhune and Dell'Apa (2006)
DWA242 (multielement ascending whistle)	100-4,000		Pahl et al. (1997)
DWA235, single ascending whistle (WA)	100-500		Pahl et al. (1997); Terhune and Dell'Apa (2006)
flat tone (O), W11	1,000-3,000		Terhune and Dell'Apa (2006)
WD10, falling chirps (W2, W3,	100-15,000		Moors and Terhune (2004)

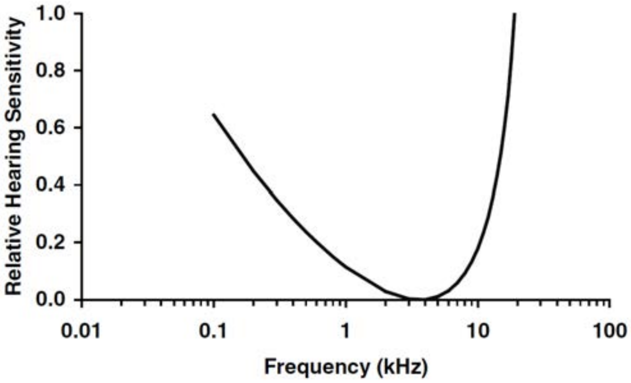
W4)			

5 Hearing capabilities of considered species

Hearing capabilities of the considered species are essential for modelling of masking. Hearing tests have been carried out on a number of cetacean species, but only few on Antarctic species.

For Mysticetes no audiogram exists. Nevertheless there have been attempts to estimate how sensitive their hearing is by evaluating their vocalisations or predicting their best hearing range. Attempts based on vocalisations are reviewed in Gill and Evans (2002) suggesting, that at least some baleen whales can hear from very low Hz to the ultrasonic range above 20 kHz probably up to 30 or 40 kHz. Those estimates are very broad and only provide insight into a probable hearing range, but do not give good indices about a general sensitivity of the animals to sound. Recent research has focused on estimating hearing capabilities by 1) establishing methodologies for measuring hearing curves without cooperation, as needed for behavioural audiograms (Ridgway and Carder 2001) and 2) combining anatomical research with modelling approaches (Houser et al. 2001). One estimated relative hearing curve from Houser et al. (2001) for a humpback whale is given in Fig. 5-1. Tubelli et al. (2012) undertook a similar work for minke whales *Balaenoptera acutorostrata*.

Fig. 5-1 Relative hearing sensitivity function of a humpback whale derived from a bandpass filter-bank model of its auditory sensitivity (from Houser et al. 2001)



Another approach is to simulate or predict the best hearing range of a baleen whale species based on an acoustic power-flow model which breaks down the auditory system into three components: one for the external ear, one for the middle ear, and one for the inner ear (Rosowski 1991; Ruggero and Temchin 2002; Tubelli et al. 2012). By evaluating the middle-ear transfer function (using finite element modelling techniques) in conjunction with cochlear properties and the sound pressure transformation occurring in the outer ear this modelling provides a more complete estimate of the audiogram. The predicted range of best hearing sensitivity (-40 dB off the maximum sensitivity) for a minke whale matches well with the vocalisation range of this species. Another comparable approach was taken by Parks et al. (2007b) using morphometric investigation of the inner ear of baleen whales (North Atlantic right whales) predicting a hearing range of 10 Hz to 22 kHz.

Audiograms of odontocetes and pinnipeds from Antarctica, together with some of closely related species (to Antarctic marine mammals), have been compiled and are given in Fig. 5-2 and Fig. 5-3.

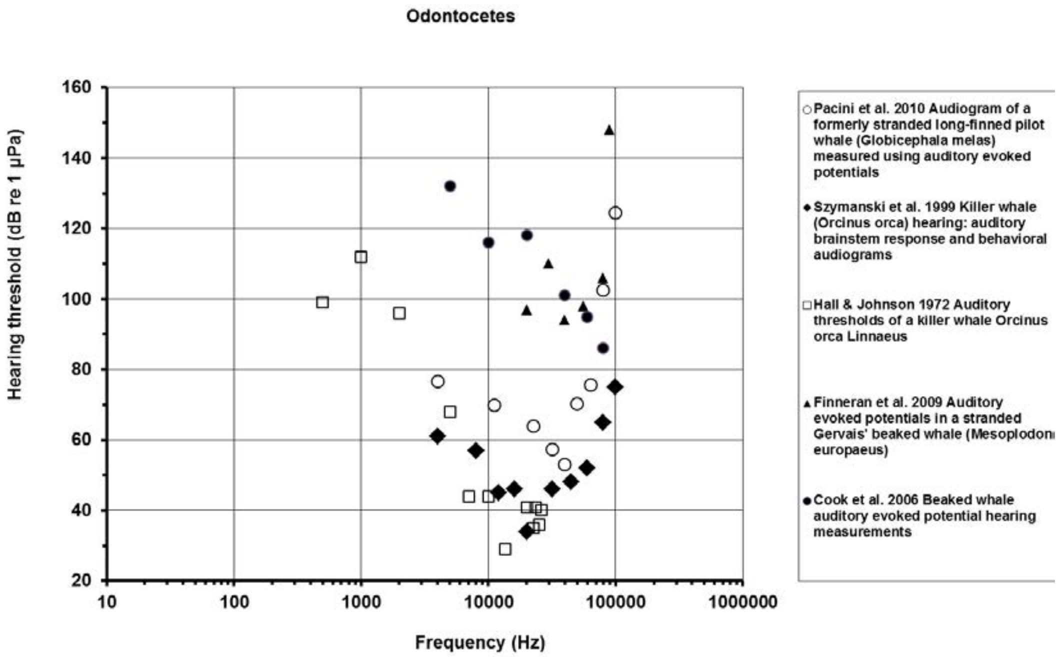


Fig. 5-2 Hearing thresholds of different odontocete species (compiled by TNO)

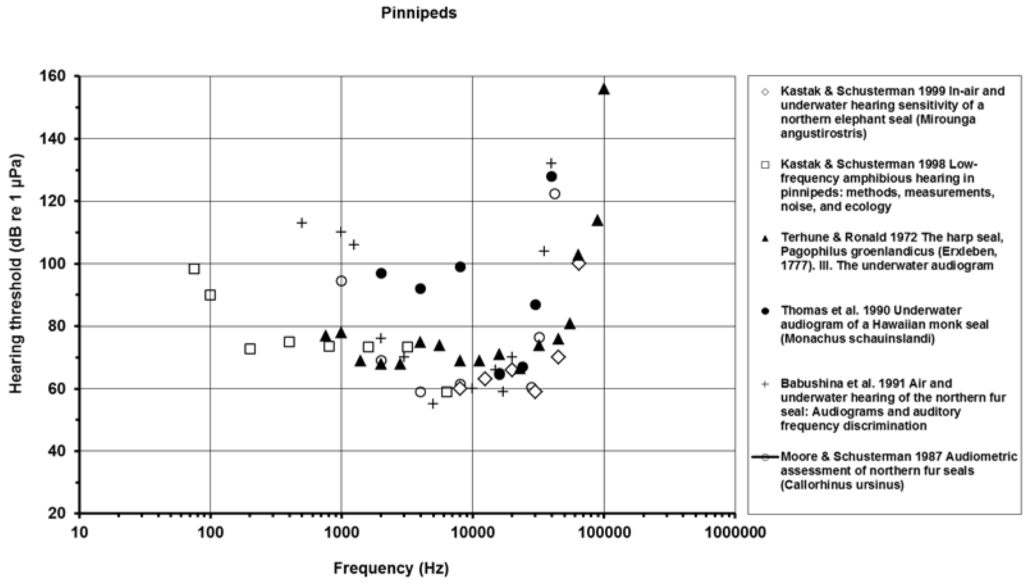


Fig. 5-3 Hearing thresholds of different seal species

Finally, some information on hearing sensitivity in species unavailable for testing could be deducted from other species. However, Gisiner (1998) notes, that inferring data from related species might not be an adequate approach. Especially extrapolating from terrestrial mammals does not seem to be helpful. Another important point is that pinnipeds are adapted to underwater vocalisation and hearing, as well as terrestrial. In-air hearing capabilities and underwater hearing capabilities are often found to have large differences, for instance there are indices that the pinniped ear is more sensitive to low frequency sounds underwater than in air (Kastak and Schusterman, 1995). Especially odontocetes exhibit the typically seen U-shape (Wartzok & Ketten, 1999; Reichmuth et al. 2013). Recently parts of an audiogram of a leopard seal were collected, but due to the situation of an opportunistic approach, only 4 frequencies (1-4 kHz) were tested (Tripovich et al. 2011).

It is assumed that the ear of baleen whales can generally be tuned like a 1/3 octave band filter (Payne and Guinee 1983). Hence the frequency content of a vocalisation adds additional information if the signal is frequency modulated – for instance as a sweep. The best case situation is achieved when a matched filter can be assumed. A technical matched filter compares a given signal to the input for instance from a hydrophone. How efficient the filter is working, hence how much improvement can be achieved in signal to noise ratio, is decided by how much variation is allowed in the difference between given and received signal. A high bandwidth of the signal is beneficial. The increase in signal to noise ratio can be estimated using a rule of thumb as it depends on the time (duration) and bandwidth (frequency range) of the given signal. However, it is currently unclear whether the hearing of baleen whales can adapt to using a matched filter on signals. For this excercise we have assumed, that when the signal is band-pass filtered in the frequency range of the given vocalisation, then a matched filter will not add much more information for the baleen whales vocalizing at low frequencies within a small range.

6 Modelling of sound propagation in Antarctica for masking studies

The main objective of this project is a first evaluation of the masking potential of airgun pulses. The original, very high level and very short airgun pulse will be modified with respect to level, duration and frequency content during propagation. It is therefore desirable to estimate the time and frequency variations induced by long range propagation. In particular frequency dependent stretching of the signal is of prime interest. There is no example for this in literature and current modelling tools allow for very limited investigations into these long ranges.

Airguns as impulsive sound sources with short duration below 1 second and comparatively low repetition rate (6 to 60 seconds) seem to have limited masking potential as only a short time interval is affected. However, simple considerations on level reduction due to geometric spreading suggest that the range at wich the signal will be heard extends into the 1000 km range (sound travelling times of more than 40 minutes). Over these long ranges and the large number of possible propagation paths, stretching of the signal increasing with range can be expected.

The following describes Antarctic conditions. Calculations comprise characteristics of the sound sources, propagation loss and resulting received levels for characteristic acoustic parameters.

6.1 General conditions

The area of interest is the Southern Ocean around Antarctica, which has a high percentage of deep sea conditions. Sound profiles and bottom conditions are defined in Boebel et al. (2009) (see chapter 3.5) and are used as the basis for the development of a new long range propagation model. Propagation was modelled for two shallow water (500 m) and two deep water (4000 m) situations. Additionally the sea conditions differ as two sound speed profiles are available, one of them showing a near surface sound duct. Four airgun configurations were used in the modelling process. However, they are only defined by their source signature as seen from vertically below. For the propagation modelling it would be desirable to have a signature which is relevant for near horizontal directions or with the contribution from surface reflection removed. Currently, the signature is available as time signal and spectrum.

Geological data are available but it is not expected that bottom reflections do significantly contribute to long range received levels for deep water, because the sound speed profile concentrates sound waves close to the surface.

6.1.1 Bottom conditions

Boebel et al. (2009) presented sediment data which have been used in numerical analysis and will also be considered here. The main consequence of the presence of a sea bottom is damping of sound waves on reflection at the sediment. This effect depends on the sound velocity of the sediment and its damping values.

Sediment parameters from Boebel et al. (2009) are P-wave (primary or compressional) velocity 1600 m/s, S-wave (secondary or shear wave) velocity 330 m/s, wet bulk density 1450 kg/m^2, attenuation of P- and S-waves Q_P, Q_S = 1.5E6 equivalent to 2.73E-5 dB/wavelength. These damping values are considered incorrect. Typical values are in the range of 100 (0.27 dB/wavelength) and 20 (1.3 dB/wavelength), respectively.

The computer code used does not use shear velocity. This is considered acceptable as sound waves being reflected at the bottom suffer a small attenuation which will nevertheless lead to complete absorption in the long ranges considered here even with only compressional sound waves alone being considered, see e.g. Fig. 6-11.

6.1.2 Sound velocity profiles as used in the calculations

The sound velocity profiles presented here (Fig. 6-1 and Table 6-1) are the basis for sound propagation modelling within the propagation modelling of airgun impulses. The diagrams are a numerical fit to the measured data.

Fig. 6-1 Sound profiles numerically fitted to stations 715 and 25 in Boebel et al. (2009) to enter numerical calculations for propagation modelling. Right hand side shows the shallow water profile.

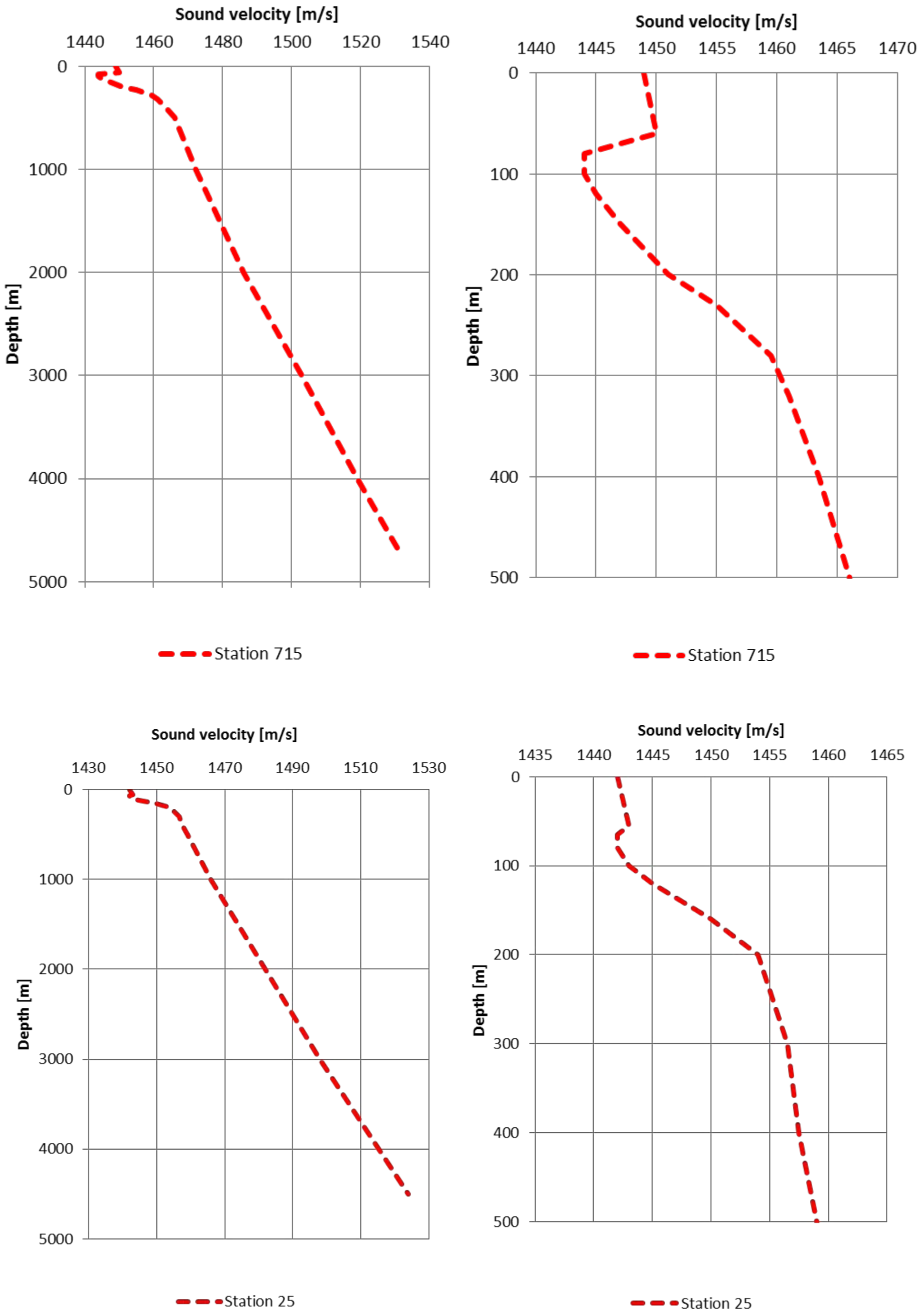


Table 6-1 Sound velocity profiles used for this study derived from Boebel et al. (2009)

Station 715		Station 25	
depth [m]	v [m/s]	depth [m]	v [m/s]
0	1,449.0	0	1,442.0
60	1,450.0	55	1,443.0
80	1,444.0	65	1,442.0
100	1,444.0	80	1,442.0
120	1,445.0	100	1,443.0
150	1,447.0	120	1,445.0
200	1,451.0	160	1,450.0
230	1,455.0	200	1,454.0
280	1,459.5	300	1,456.5
320	1,461.0	400	1,457.5
400	1,463.5	500	1,459.0
500	1,466.0	1000	1,466.0
1000	1,472.0	3000	1,498.0
2000	1,486.0	4500	1,524.0
3000	1,503.0		
4000	1,519.0		
4700	1,531.0		

6.2 Source levels and propagation loss for airgun arrays

6.2.1 Source level considerations

The ideal description of a sound source for the following calculations is a monopole, i.e. a uniformly, omni-directionally radiating sound source. This source can then be put into any medium to model propagation. The medium and environment does not have an effect on the source and the frequency content of the sound radiated.In reality the airgun does not behave like a perfect monopole in close range, but in the large distances considered here it is a good approximation. Furthermore ocean depths vary and will have consequences especially in shallow waters.

The monopole source level is the level of the source in a fictious 1 m distance in an unbounded and ideal ocean, which is represented by a so called “notional signature”. The short impulse of a point (monopole) source is characterised by a continous (smooth) frequency spectrum. The smooth spectra of the fictious monopole can then be used for propagation calculation in all vertical angles.

Breitzke & Bohlen (2010) describe 4 airgun configurations which shall be considered as sound sources for the following investigations. They are different by number, type, arrangement and tow depth.

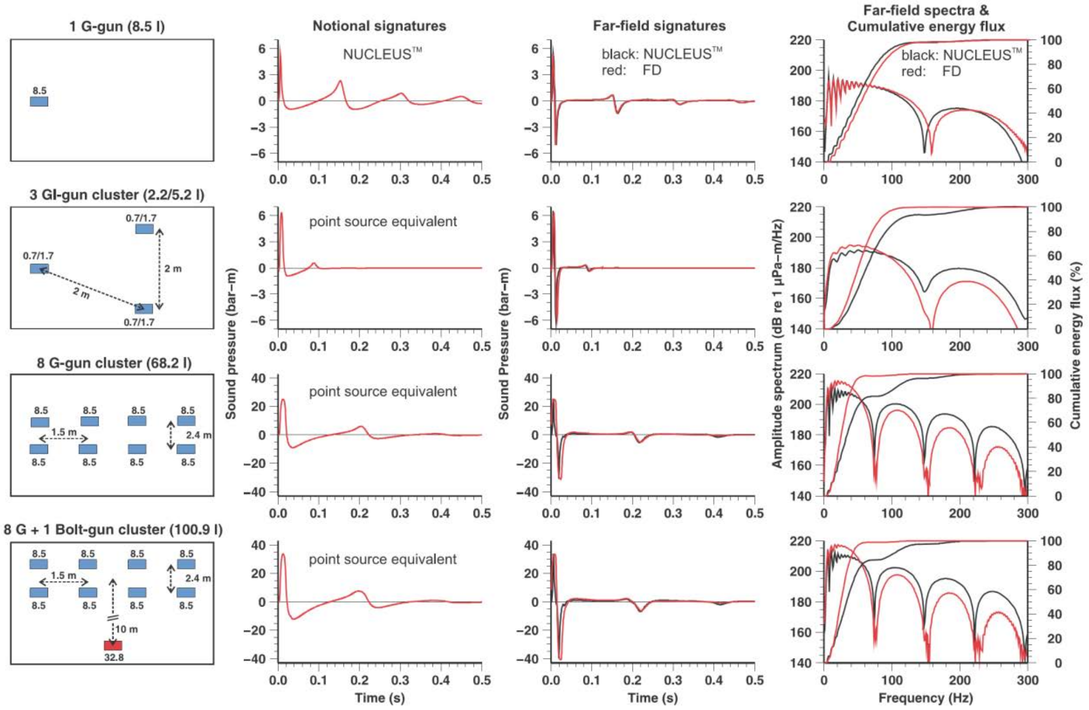
Input time signals of the notional signature for each airgun configuration as described by Breitzke & Bohlen (2010) are shown in Fig. 6-2. The digitised source time signals, the notional signature, and spectra are shown in Fig. 6-2 to Fig. 6-6. From these figures it can be inferred that the notional signature as modelled by Breitzke & Bohlen (2010) is not representing the source as a monopole except for the single G-gun because there are pronounced minima ("ghost-notches") caused by destructive interference of the directly radiated sound of the array and its surface reflection ("ghost"). At best this reflection should be removed from the signal because it will be included in the propagation calculations and would therefore be present twice in the propagation calculation.

We tried to correct the spectrum by eliminating the ghost-notches by applying a correction function for the surface reflection (Fig. 6-7). Fig. 6-8 shows that this elimination was not completely successful. Therefore, a smooth function was then extrapolated to represent the expected monopole spectrum instead of the originally given notional signature. This idealised monopole spectrum is then used for the following considerations to create a basis for plausibility checks of the modelled results.

In the following numerical modelling calculations, however, it was decided to use the time signal given by Breitzke & Bohlen (2010) to make sure that no error occurs by omitting phase information, i.e. the phase between adjacent waves of different frequencies, in the source signal. The surface effect (reflection) is contained in this signal and therefore has to be ignored. However, the overall effect on the final results is likely negligible, though it will lead to missing information at the frequency location of the ghost. This is considered to be acceptable with respect of other inaccuaries and uncertaincies of the calculations carried out.

In a later project the difference between the signal with correct phase information but with surface effect could be compared to the smooth signal with no surface effect and no phase information. With the current information it is not possible to derive a time signal without the surface reflection effect and complete phase information.

Fig. 6-2 Source description used in the propagation modelling.



Input from Breitzke & Bohlen (2010). The source description used in the propagation modelling is based on the information summarised in this figure. The notional signatures in the second column have been calculated by Breitzke & Bohlen (2010) using the MASOMO module of the NUCLEUS software and were used as source levels for the modelling in this study. The farfield time signal and spectra are shown in the last two columns. The minima (ghosts) in the spectra are a consequence of destructive interference of the direct signal and the surface reflected signal. The notional signal also contains this interference except for the single G gun which is a true monopole.

Fig. 6-3 Source signature (time signal or wave form) in 1 m distance for all array configurations (from Breitzke und Bohlen, 2010)

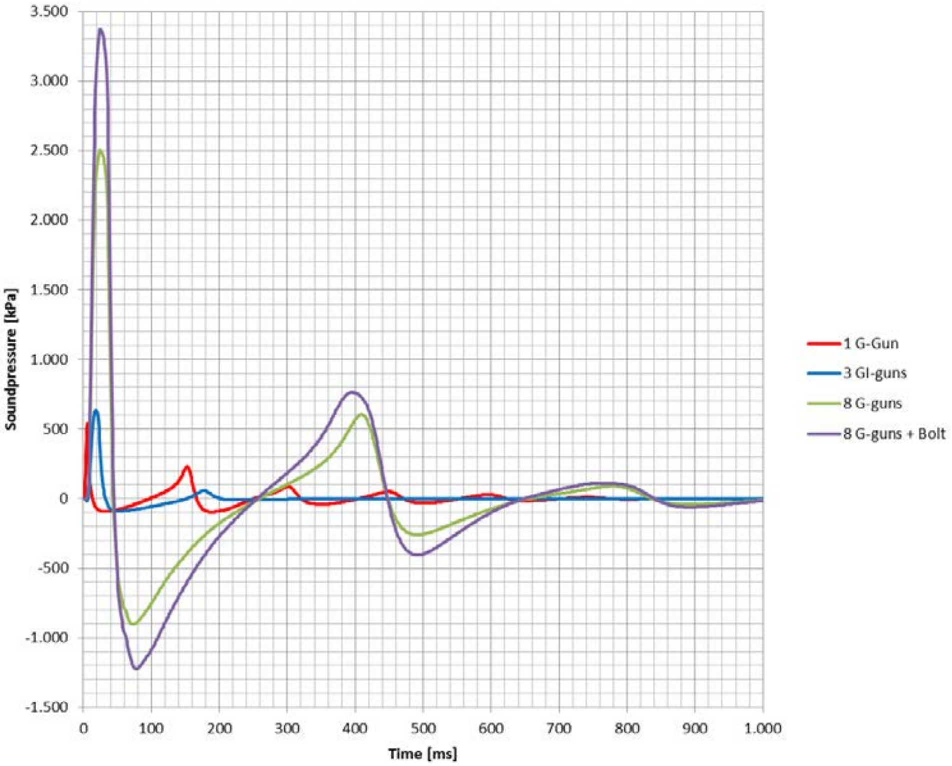


Fig. 6-4 Frequency spectra for the time signals of all considered airgun configurations.

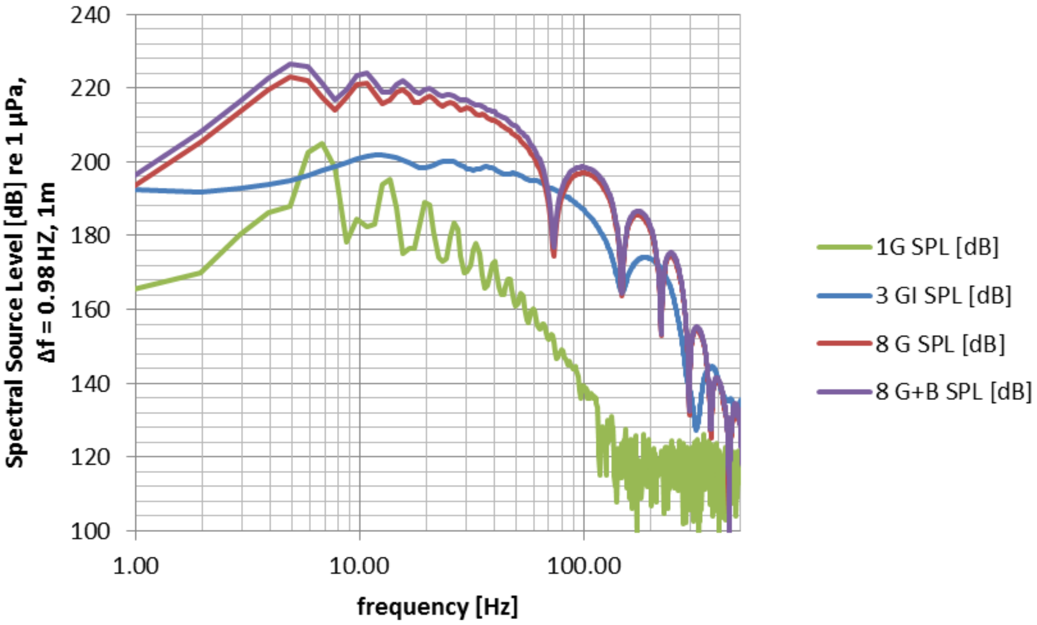
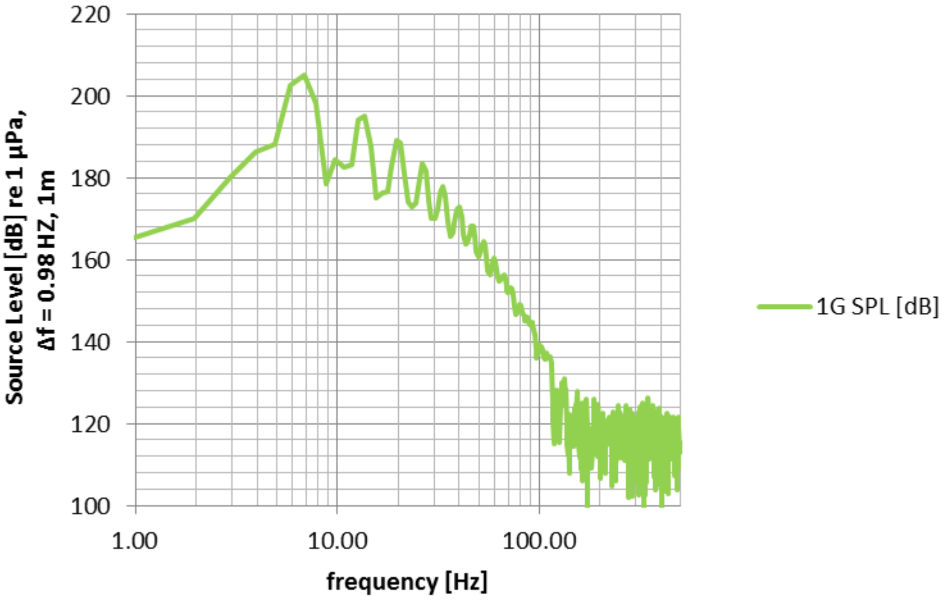
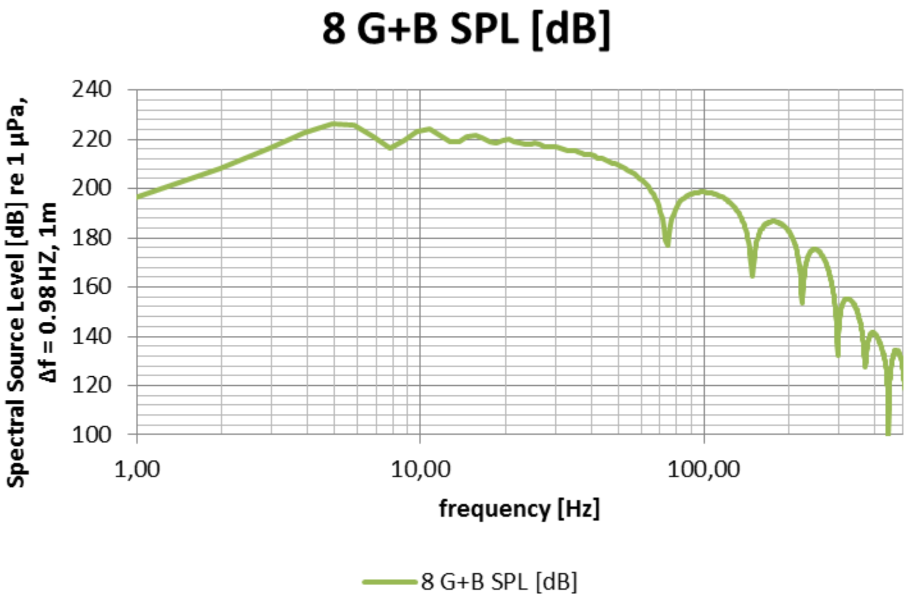


Fig. 6-5 Spectrum of a single G-gun with a volume of 8.5 l.



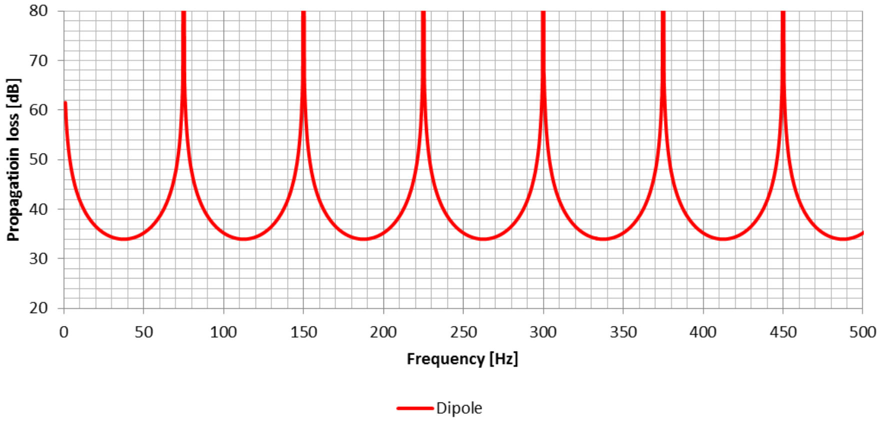
The ripples are harmonics of the bubble oscillation frequency. Above 100 Hz the signal seems to be covered by a noise floor.

Fig. 6-6 Spectrum of an array consisting of 8 G-guns and 1 bolt gun.



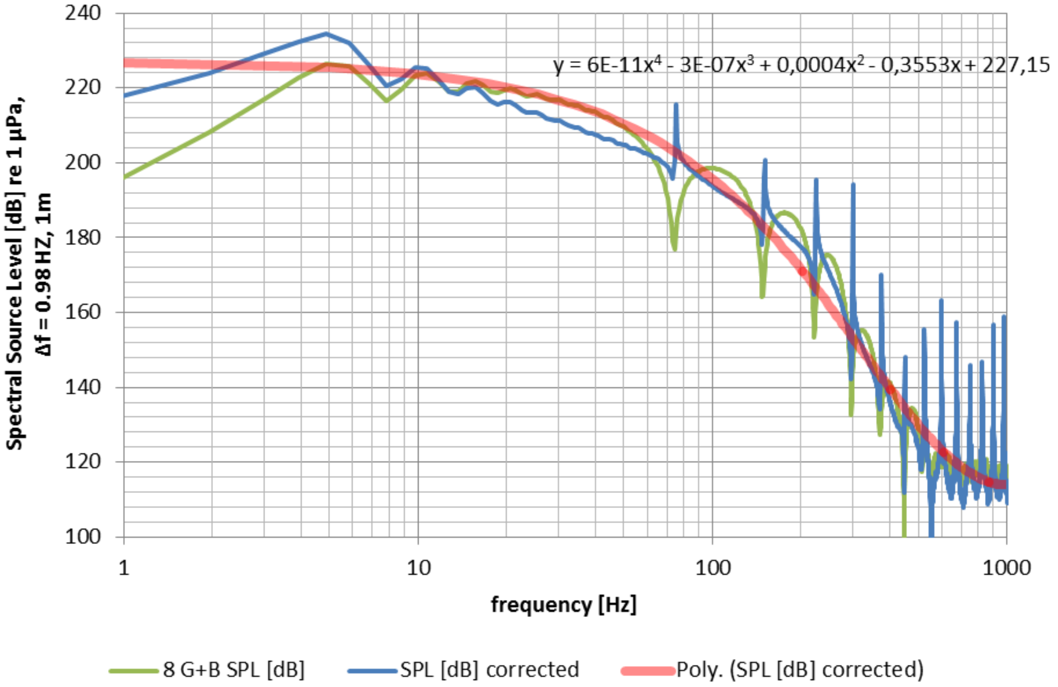
Spectrum of an array consisting of 8 G-guns and 1 bolt gun with a combined volume of 100.9 l. Only few ripples occur but pronounced effects from the surface reflection can be seen.

Fig. 6-7 Propagation loss of a point source located 10 m below the surface as seen from 100 m vertically below.



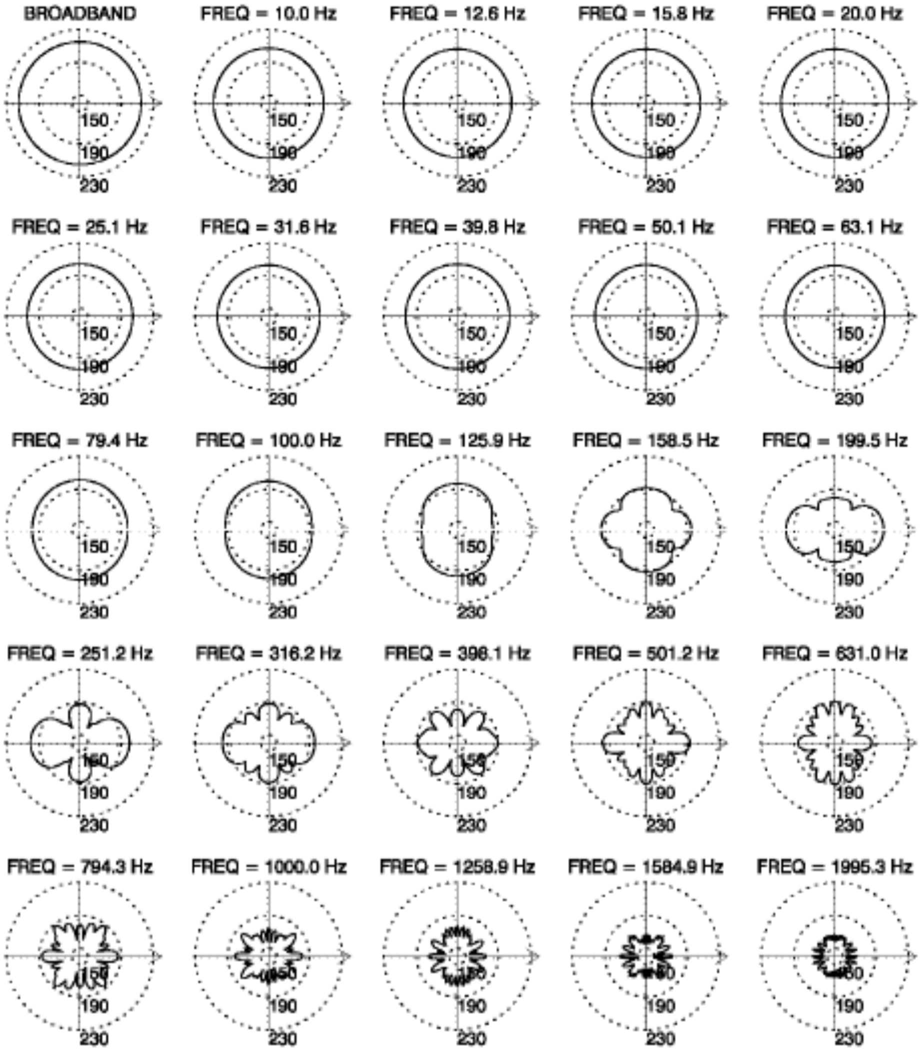
From the propagation loss shown in Fig. 6-7 the spherical transmission loss 20 log (r) is substracted (40 dB) which yields a correction function for the notional signature without surface influence. The correction is not perfect because obviously the minima in the notional signature („ghost notches") do not have the exact same shape as the transmission loss. The resulting smooth trend shown in Fig. 6-8 is assumed to be a reasonable approximation to a monopole source level. However, as it is not the result of a Fourier transform there is no phase information which will be needed for the calculation of signal stretching. Therefore these spectra can only be used in considerations in the frequency domain.

Fig. 6-8 Source level of Fig. 6-7 corrected for spherical transmission loss (minus 40 dB) and a resulting smooth trend line (Poly.) as a representation of the spectrum used for the plausibility check of propagation modelling.



Airgun arrays are generally designed according to their performance in vertical direction. It is impossible to derive the signature in other directions as there will be an additional interference pattern due to the signals from the individual airguns which are not arriving at a receiver at the same time. The horizontal patterns shown in Fig. 6-9 which is caused by this lateral distance are not accounted for. As we will see later on: the effect of this simplification is ignored respectively assumed to be worst case. When we assume that the array configurations considered here have a similar pattern as the one in Fig. 6-9, the directivity is not uniform above 120 Hz. So, the assumption that the source spectrum is the same in all directions is conservative.

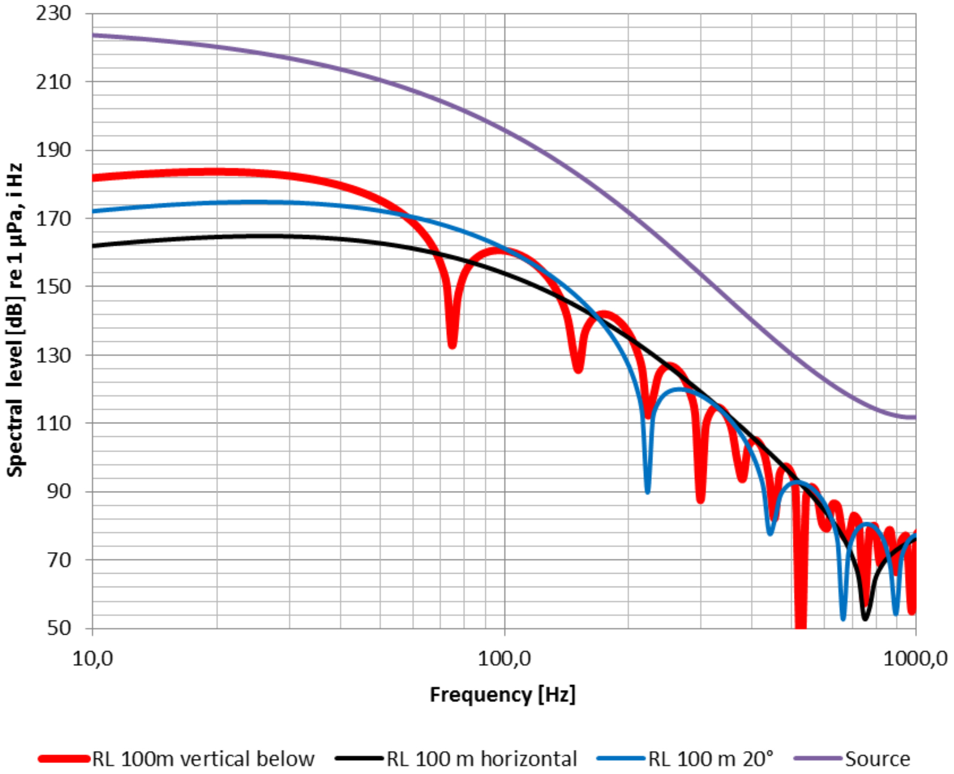
Fig. 6-9 Horizontal directivity patterns of an airgun array.



Source levels are given in dB re 1 µPa, from MacGillivray (2006). This configuration was not considered in this study, but demonstrates the fluctuation of the level in the horizontal axis above a certain frequency where single airguns interfere with each other. Directivity is not considered because it is not a crucial factor for this study.

A simple calculation as demonstrated in Fig. 6-10 reveals the difference of received level with variation of the vertical angle. In exactly horizontal direction the first ghost notch is just at around 750 Hz. Only at very low frequencies below about 150 Hz there is a systematic difference in received levels. This effect is, however, ignored in the following, as this interaction will lead to lower source levels because coherent sources yield the highest possible source level. Quantification of the degree of level reduction is not possible with current knowledge.

Fig. 6-10 Source level and example received levels (RL) for various vertical aspects.



The horizontal source level (sound pressure level - SPL) in Fig. 6-10 equates to approximately the following formula. Frequency f in Hz:

EQ 1: $SPL[dB]re1\mu Pa = 9\cdot 10^{-11}\cdot f^{4} - 3\cdot 10^{-7}\cdot f^{3} + 0.00045\cdot f^{2} - 0.3553\cdot f + 227.16$

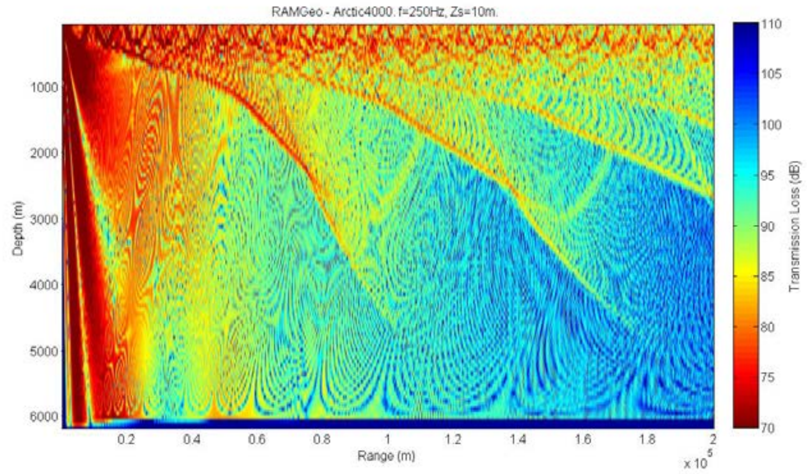
The SPL resulting from EQ 1 can be used as input source level (in the frequency domain) and serves as input for a plausibility check, see Fig 6-15. There is obviously no time signal representing this spectrum. In the following, numerical calculations will be based on the FFT derived from the time signals to avoid conflicts with missing phase information when applying EQ 1. The complex spectrum will therefore have gaps at frequencies where the ghost notches are, see e.g. Fig. 6-17 at 75, 150 Hz or the white bands in Fig. 7-19. For prediction of masking this effect is considered not important as total energy radiated is hardly affected.

6.2.2 Results for estimation of propagation loss

The following is an approach to estimate propagation loss as a basis for ensuring plausibility of the results of the numerical calculations. This is carried out by looking at the sound field and the use of simple models to estimate received levels using the source levels described in the previous chapter. The Appendix B shows various plots for transmission loss (TL) up to 2000 km. The general observation is:

- Above 125 Hz a pronounced surface channel is observed after the overlaying sound waves from bottom reflection subside due to damping in the bottom.
- Below 63 Hz TL is higher than at higher frequencies; presumably due to the source being in close vicinity of the surface (Lloyd-Mirror-Effect).
- TL is in the order 90 to 100 dB at 2000 km for frequencies considered here, see Appendix B.

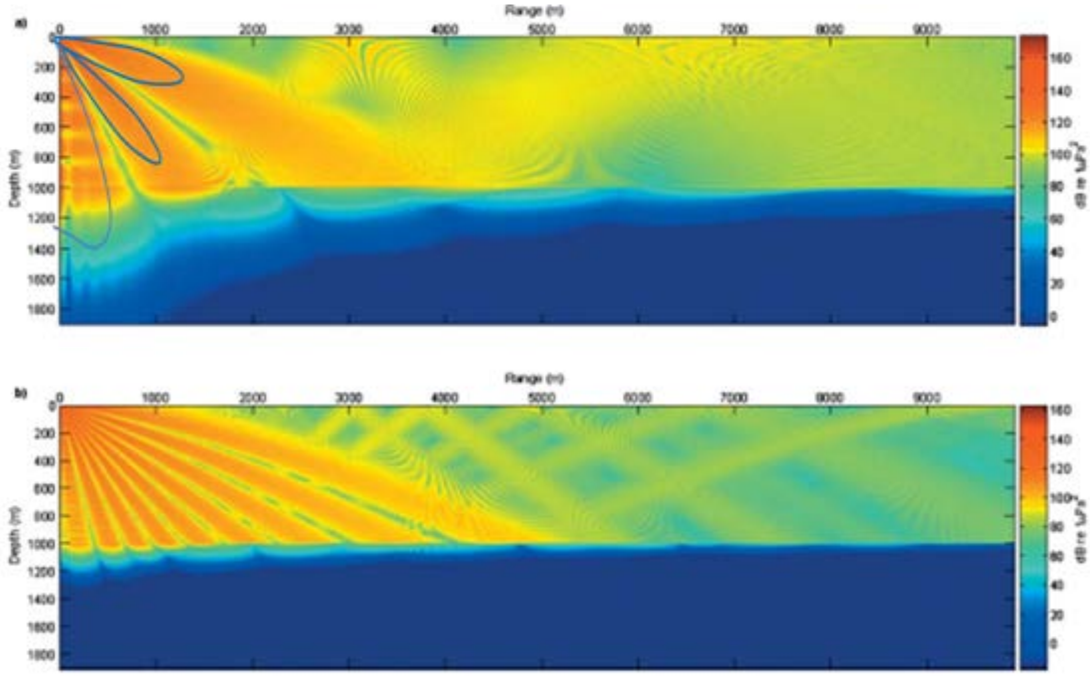
Fig. 6-11 Sound field for a distance of 200 km and a frequency of 250 Hz.



Example: The sound field for a distance of 200 km and a frequency of 250 Hz. Note that the main propagation path is along the surface which will be the case for both velocity profiles.

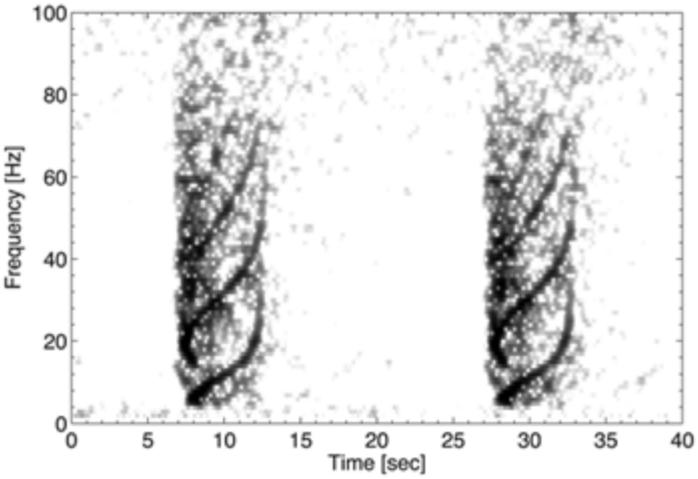
The following two pictures are further indications as to the nature of sound propagation and expected results. Fig. 6-12 shows the beam pattern of a noise source close to the surface. The beam pattern is a consequence of the Lloyd-Mirror-Effect. It can be seen qualitatively how the intensity of the noise field reduces after reflection on the bottom. Fig. 6-13 shows a spectrogram of a received signal measured in the field. A characteristic upsweep is obvious but there is also a downsweep faintly visible. This pattern is a consequence of different modes arriving at the reciever at different times.This measured result compares favourably to the modelled propagation results for airgun pulses in this study, see e.g. Fig. 7-18ff.

Fig. 6-12 Beams of a point source close to the surface at higher frequencies.



A modeled received pressure level for 300 and 1000 Hz from Tashmukhambetov et al. (2008), with overlay (blue line in a.) of own calculation of the propagation pattern. Note strong absorption of the reflected beams at the bottom.

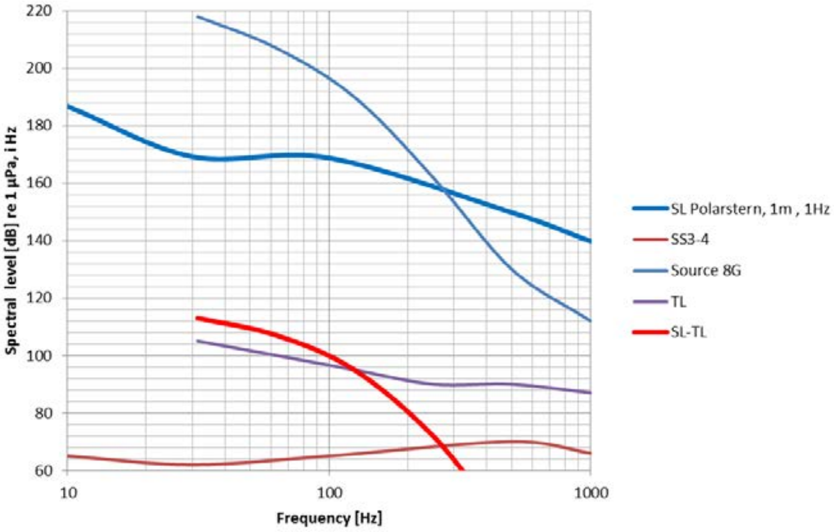
Fig. 6-13 A possible result of propagation modelling: Airgun shots registered in the Chukchi Sea (from Roth et al. 2012).



6.2.3 Results for estimation of received levels

With the source levels and the results from propagation (transmission) loss a rough estimation of the received level at 2000 km distance can be made. Fig. 6-14 shows source and received level of an airgun array and, for comparison vessel self-noise of RV Polarstern (from Boebel et al. 2009). Although the impulse of the airgun and the continuous noise from background and Polarstern are difficult to compare, it is possible with 1 Hz bandwidth and a signal of 1 s duration with L_{eq} (Equivalent Continuous Sound Pressure Level) equaling SEL at least numerically. L_{eq} of the received airgun array would be 10 dB less if the signal is 10 s long but would still be far above background noise assuming that this would be equivalent to sea state 3-4 (SS 3-4). Even a single small ("quieter") airgun (20 to 40 dB lower in level than the loudest) would still remain above background noise level in 2000 km distance.

Fig. 6-14 Received level at 2000 km.



Received level at 2000 km (i.e. the difference between Source Level SL and Transmisson Loss TL, red line) in comparison to the background noise at seastate 3-4 (SS 3-4). This will serve as a rough plausibility check for the following calculations.

6.2.4 Modelling propagation loss and signal stretching

The frequency components of the spectrum of an airgun impuls travel along different propagation paths to the receiver.

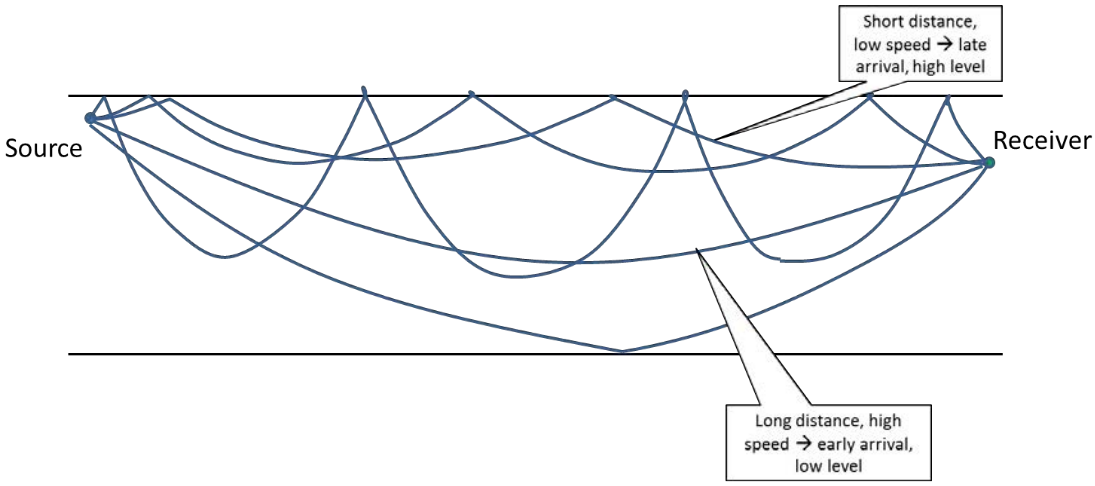
The sound speed in the Antarctic has a positive gradient with depth, i.e. the speed of sound increases with depth (see Fig. 6-1). In summer there is a small layer with a negative gradient but in essence, this has only limited effect on sound propagation. However, because of this sound speed profile, sound waves are refracted upwards towards the water surface as waves on the top are slower than in the deep. This leads to a concentration of sound energy close to the surface.

There are only a limited number of propagation paths, also called modes, between a source and a receiver. Each mode goes along with a certain vibration shape of the water body. For each of the frequencies the mode shape is a bit different, which leads to the effect that modes propagate at different speeds (frequency dispersion). Further, different propagation paths lead to different travel distances and different average sound speeds. For example a sound wave going very deep below the surface travels a longer distance than one close to the surface but travels most of this distance in water with a higher sound speed than present on the surface. As a consequence this sound wave arrives early because of the high speed but with a low level because of the larger distance it travels. On the other side a wave travelling close to the surface arrives with a high level but is comparatively slow. The effect is called mode dispersion.

Frequency and mode dispersion increase with distance, leading to stretching of any short impulse up to signal of significant length of more than 10 seconds at a distance of 2000 km.

In environments were the sediment plays a major role, in our case the environment with a sandy bottom in 500 m depth, matters are more complicated because of its frequency dependent absorption behaviour. In this case time stretching may not increase proportionally to distance.

Fig. 6-15 Mode dispersion.

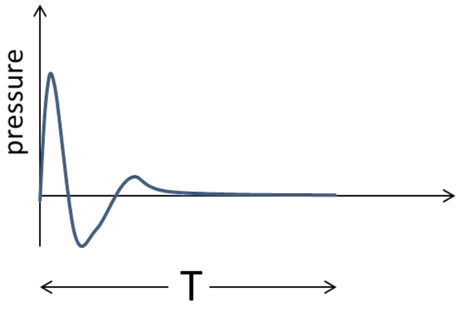


Example for different propagation modes in water with a positive sound speed gradient. The upper boundary is the water surface, the lower is an absorptive bottom

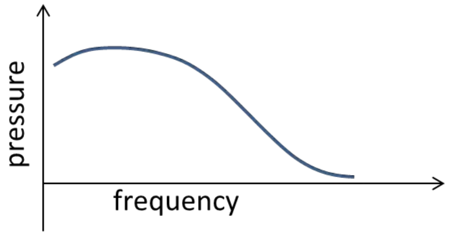
For the propagation calculation we used the freely available software AcTUP (Acoustic Toolbox User-interface & Postprocessor). This software wraps several sound propagation codes in a common pre- and postprocessing environment. At first, an idea of to how much the signal stretching can be expected from results of AcTUP indicating group velocities for each mode, was developed.

Correct calculations of signal stretching require the following steps:

1. Input time signal to Fast Fourier transform (FFT) with amplitude and phase. For the orignal time signal see Fig. 6-15. We have to use them despite being not the real source levels.



Time signal (wave form) of source

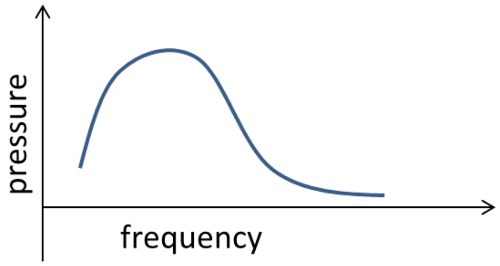


$$* \; e^{i\omega\tau}$$

Spectrum of source from time signal by FFT

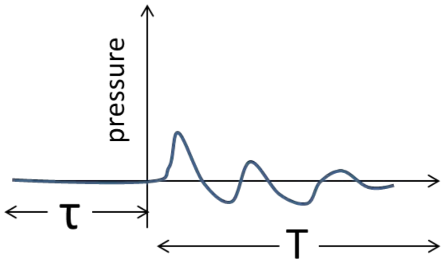
Calculate transmission loss

2. Calculate received spectrum from source level and transmission loss



Spectrum of received signal in distance x calculated by propagation code of AcTUP

3. Calculate the inverse transform to get received time signal



Received time signal from received spectrum by inverse FFT

With increasing frequency and range, the number of calculations for the transmission loss leads to large calculation times, because frequency resolution is inversely proportional to the duration of the signal, e.g. signal stretching to 5 seconds requires a frequency resolution of 1/5 Hz, i.e. 5000 frequency steps for each calculation case.

Another problem is the travel time in itself, which needs to be suppressed when calculating the inverse FFT.

Note that for the time signal of 1 second duration the frequency resolution is 1 Hz. The sampling frequency determines the maximum frequency calculated. The FFT of the frequency f_m of the time signal x (amplitude at frequency m) is:

EQ 2:

$$f_m = \sum_{k=0}^{2n-1} x_k \cdot e^{-\frac{2\pi i}{2n}mk} m$$

where x_k is the complex sound pressure (i.e. with amplitude and phase) at time step k.

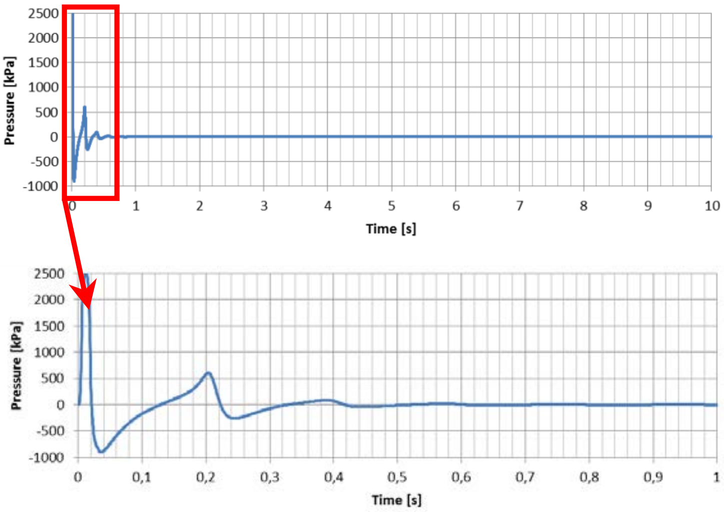
EQ2 will yield a complex amplitude (i.e. including phase information) for each frequency. Using AcTUP TL is calculated for each individual frequency. The result is a complex value for the sound pressure difference between source and receiver location constituting the received spectrum. A problem with this procedure is, that there is a certain time lag until the signal arrives at the receiver. If this is not accounted for the resulting time signal will be zero because only the first second of the signal will be displayed. To overcome this, the f_m above will be multiplied with the factor $e^{i\omega\tau}$ where i is the square root of -1, ω is the angular frequency and τ is the travelling time of the signal. The received spectrum is then transferred to a time signal by inverse FFT.

The following are representative results for single impulses for a specific set of parameters (as listed below). The results for all calculated conditions and geometries are presented in Appendix B. The time signal of the source is given in Fig. 6-16.

Note: all time signals are described in linear pressure [Pa], all spectra in SEL [dB] re 1 µPa. Often instead of 1 µPa the reference is given as µPa²s. The levels are the same.

Source	8 G-guns
Sound speed profile station 715 down to	500 m
Water depth	500 m
Source depth	10 m
Receiver depth	10 m
Compressional speed of sound (bottom)	1600 m/s
Density of bottom	1480 kg/m³
Damping	0.3 dB/λ
water surface	flat
Calculation code	Mode summation

Fig. 6-16 Input time signal of an 8-Gun-Array.



6.3 Result for single airgun shots

In the following chapter the results of signal stretching for all calculated distances are depicted.

6.3.1 Results for 100 km distance

Fig. 6-17 Source spectrum and received spectrum (at 100 km distance) of the 8-G-gun array.

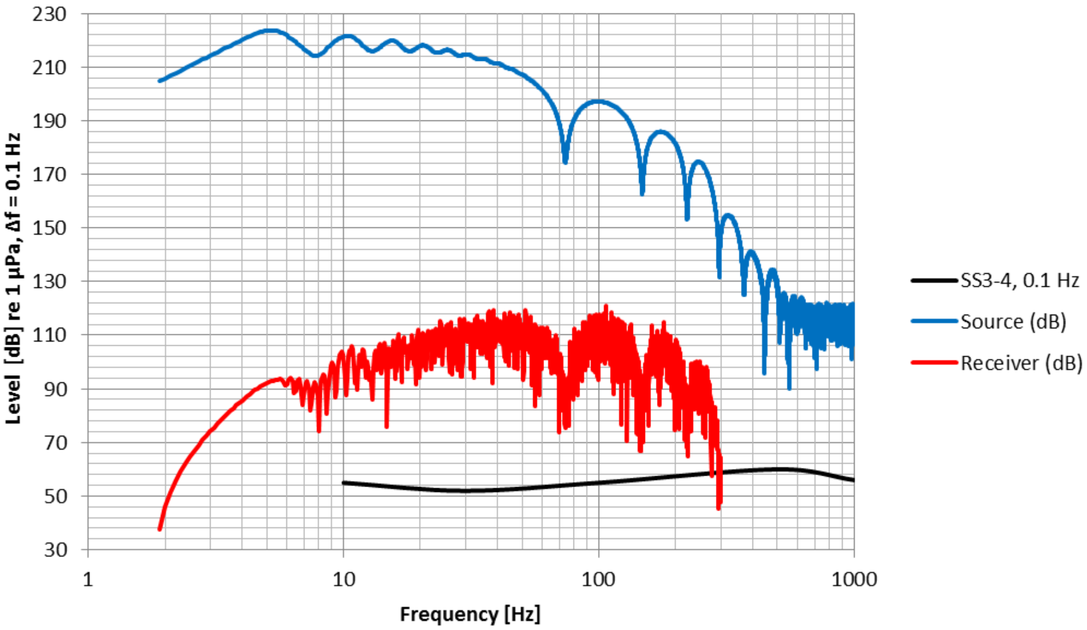
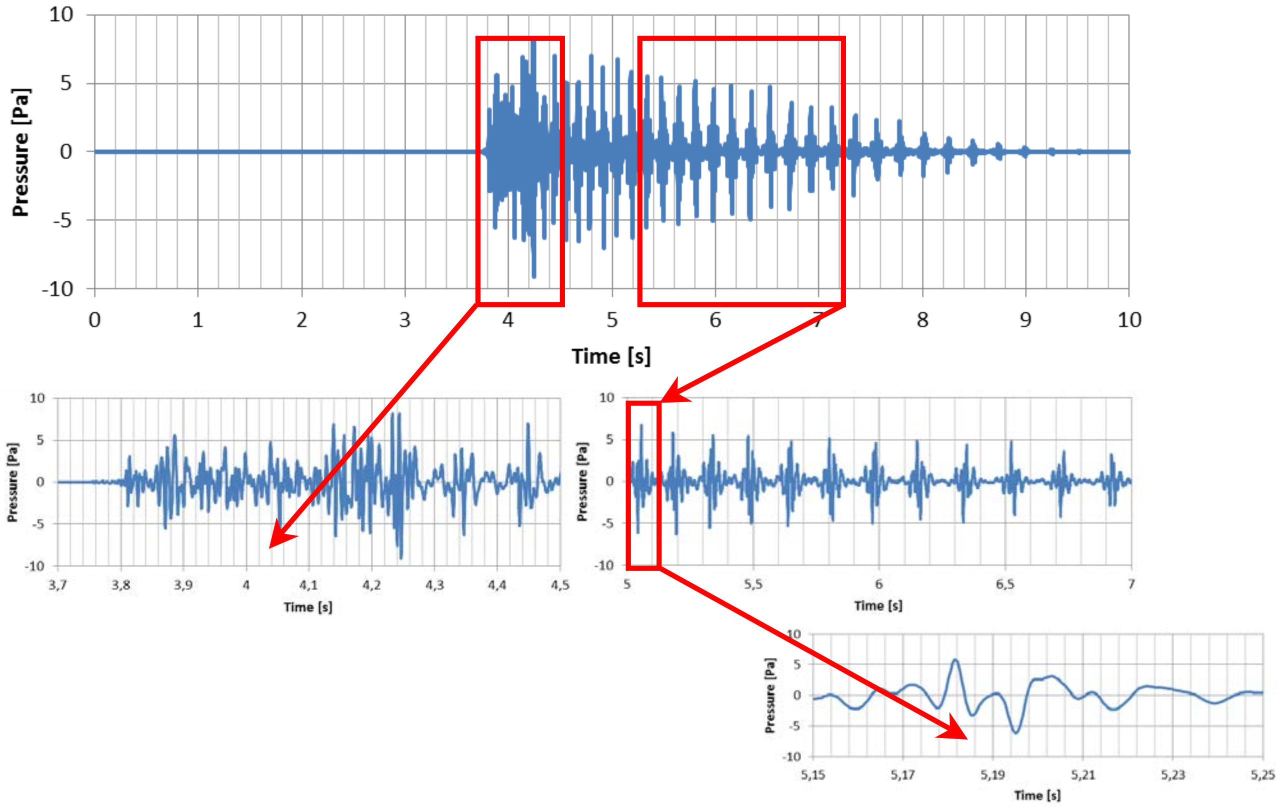


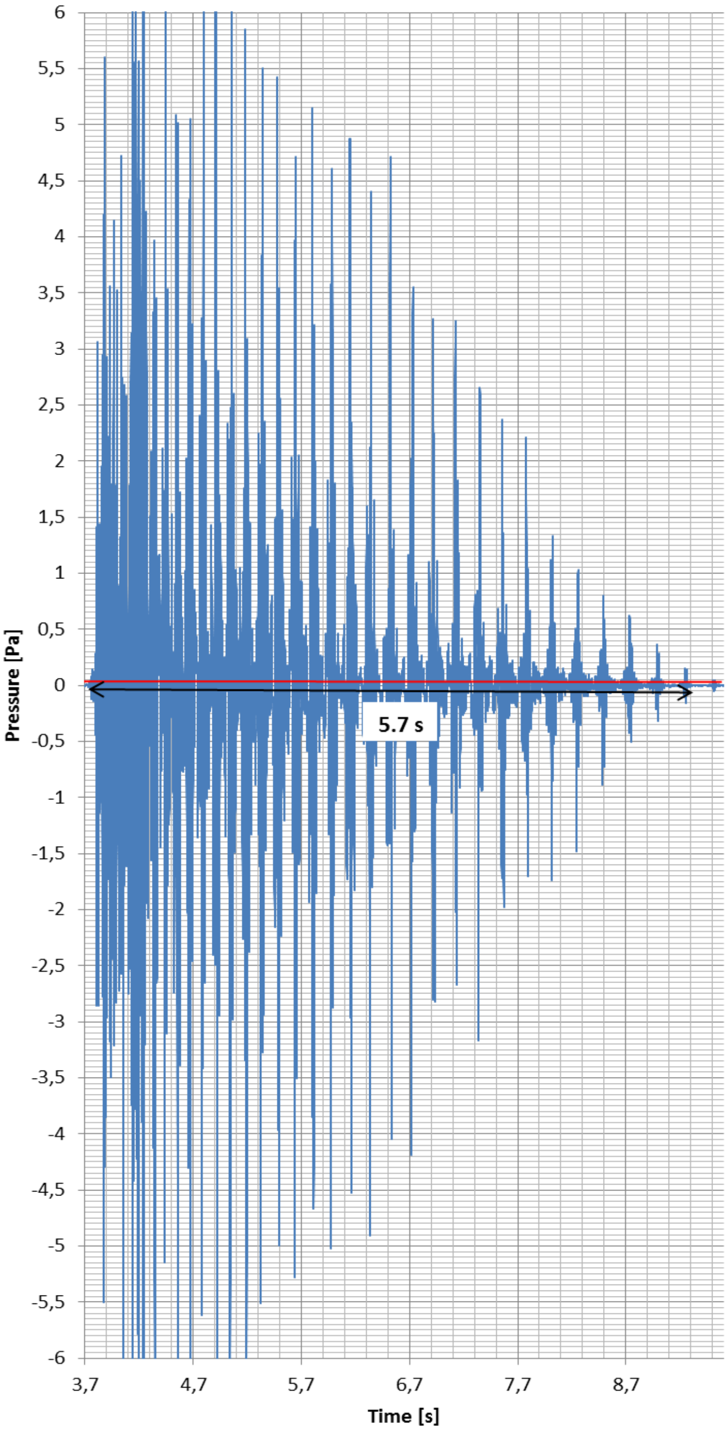
Fig. 6-18 Received time signal at 100 km.



Received time signal at 100 km with expanded displays in selected areas. It can be seen that there are parts with fairly continuous wave forms and sequences with impulsive sound.

The wave form is stretched to almost 6 seconds after 100 km (Fig. 6-18). The received spectrum is still 60 dB above background noise (Fig. 6-17). However, the received spectrum is made out of a time signal of 6 seconds duration. To estimate whether background noise may reduce this duration, we calculate the time signal of background noise by summing up all frequencies between 10 and 300 Hz. This leads to an average pressure amplitude of about 0.03 Pa. This is too low to significantly limit the time signal before it drops below background.

Fig. 6-19 Expanded View of extended signal at 100 km distance.



The signal is 5.7 s long before it drops below background noise indicated by red line which is equivalent to a time signal with 0.03 Pa amplitude using the frequency band from 10 to 300 Hz.

6.3.2 Results for 500 km distance

Fig. 6-20 Source spectrum and received spectrum (at 500 km distance) of 8-G-gun array.

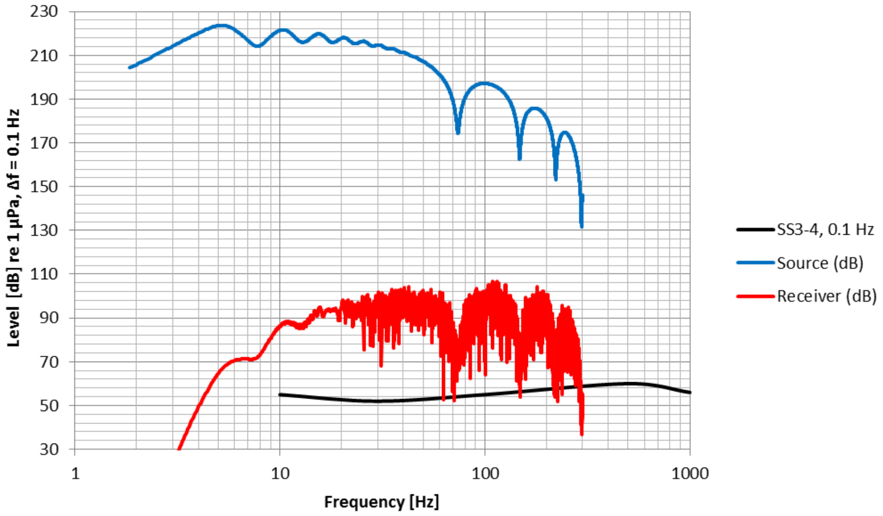


Fig. 6-21 Received time signal at 500 km distance.

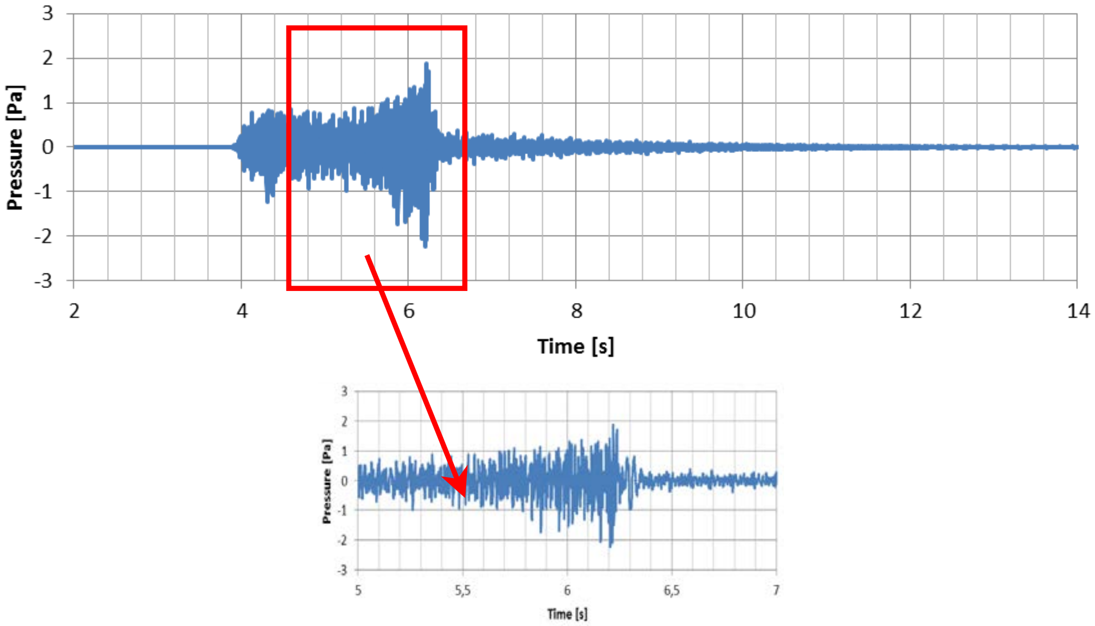
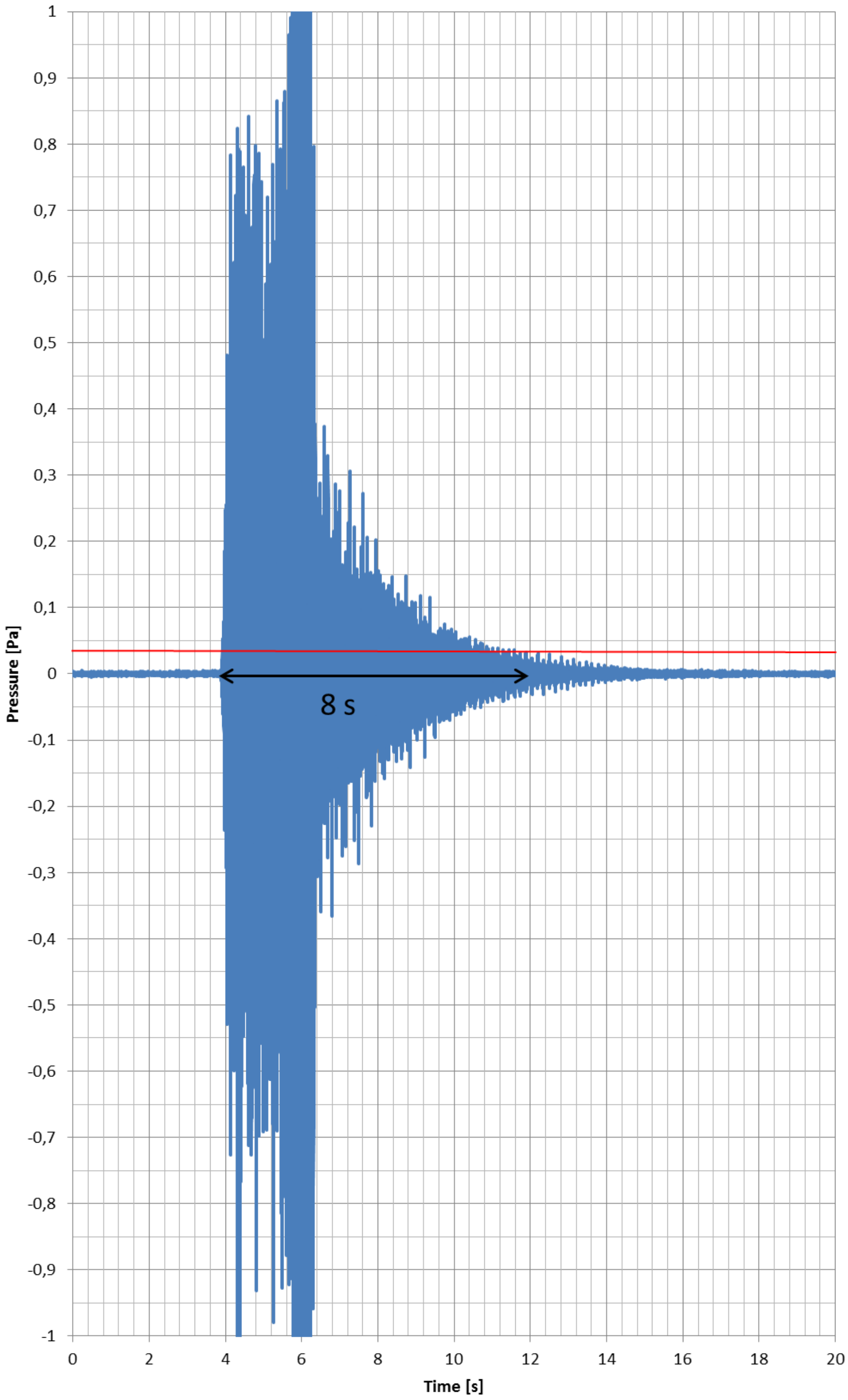


Fig. 6-22 Expanded view of extended signal at 500 km distance.



The signal is 8 s long before it drops below background noise indicated by red line which is equivalent to 0.03 Pa.

6.3.3 Results for 1000 km distance

Fig. 6-23 Source spectrum and received spectrum (at 1000 km distance) of 8-G-gun array.

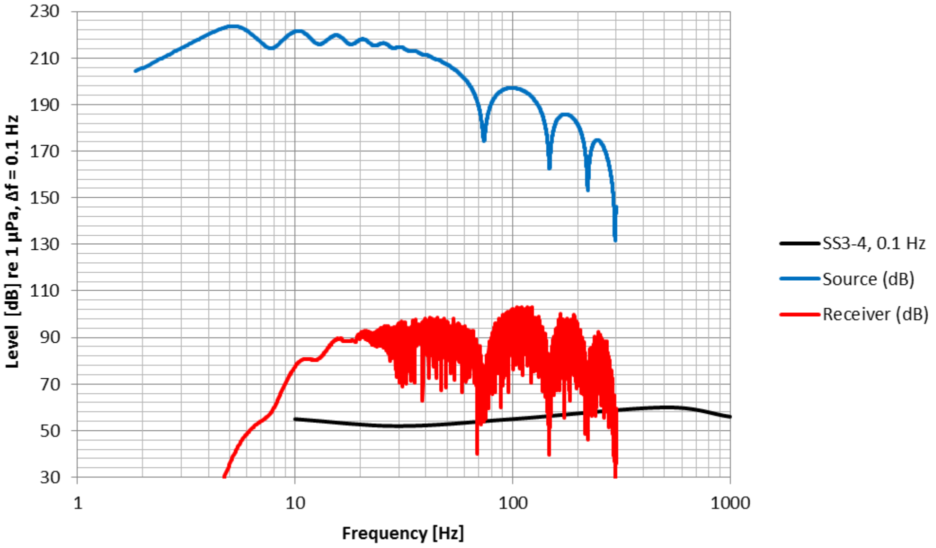


Fig. 6-24 Received time signal at 1000 km distance.

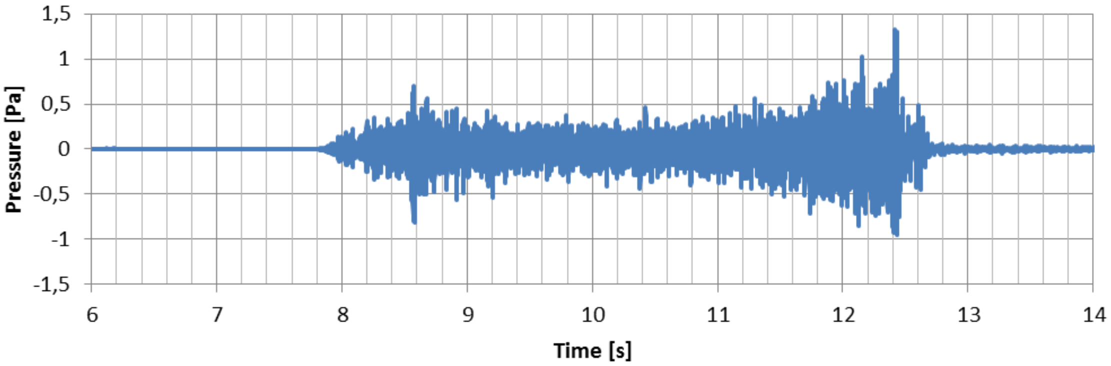
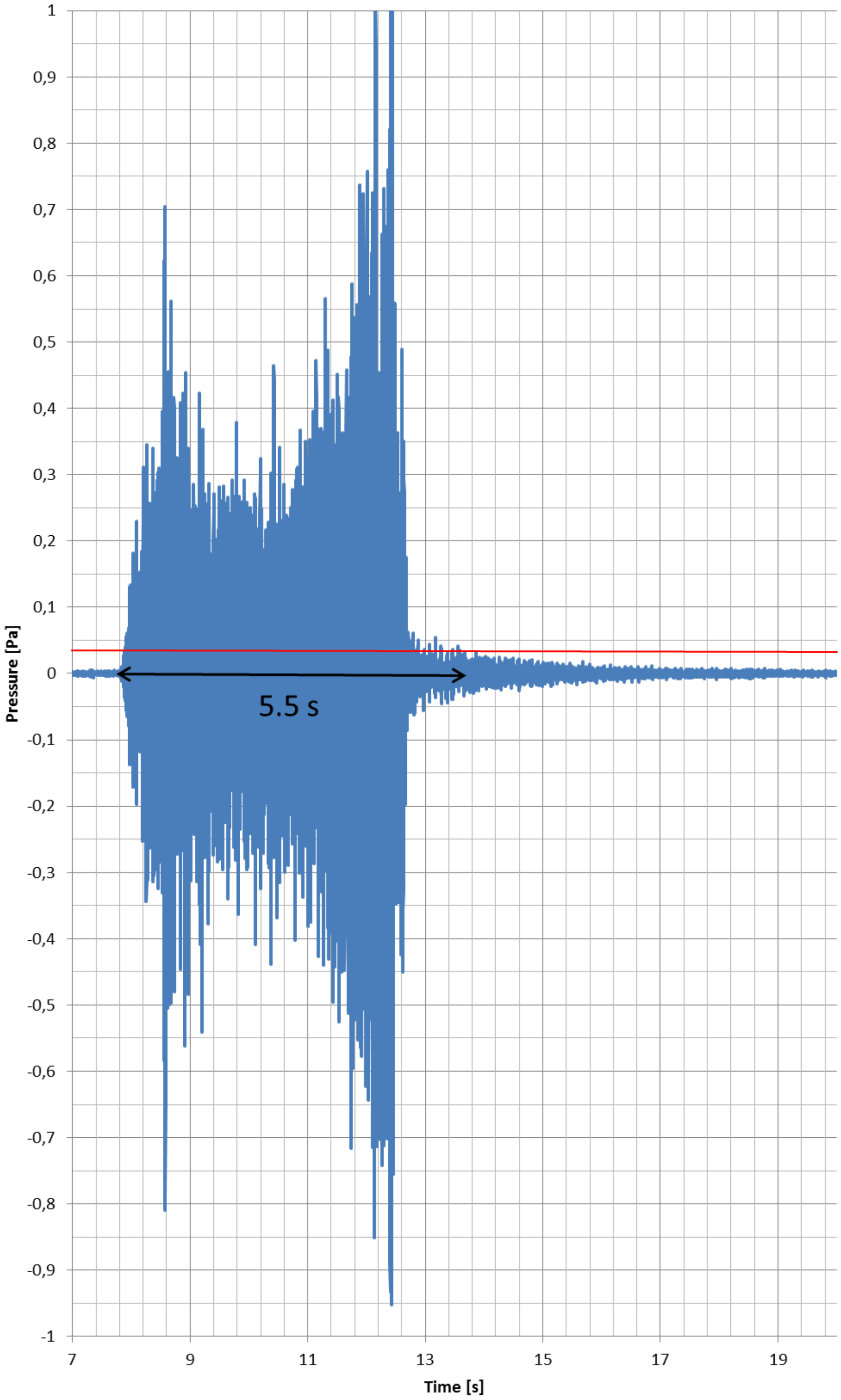


Fig. 6-25 Expanded view of extended signal at 1000 km distance.



The signal is 5.5 s long before it drops below background noise indicated by red line which is equivalent to 0.03 Pa.

6.3.4 Results for 2000 km distance

Fig. 6-26 Source spectrum and received spectrum (at 2000 km distance) of 8-G-gun array.

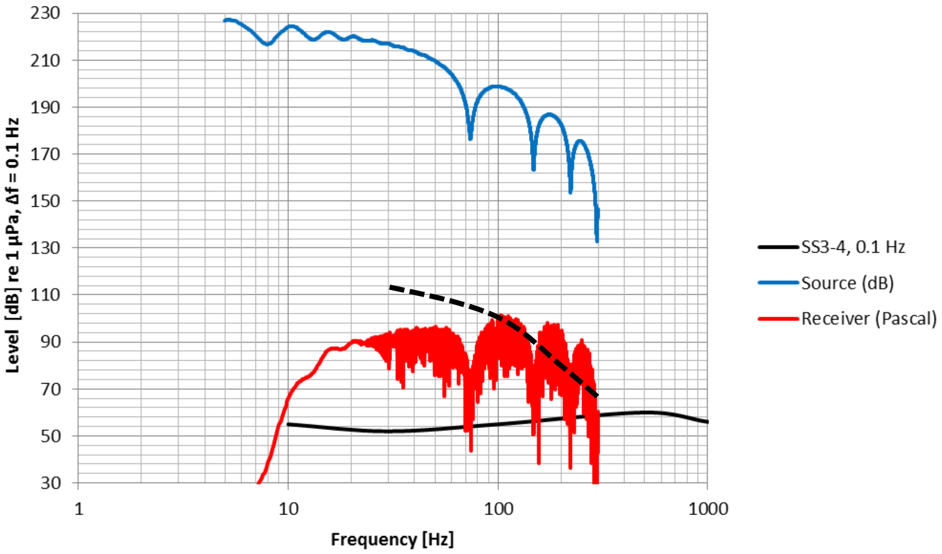
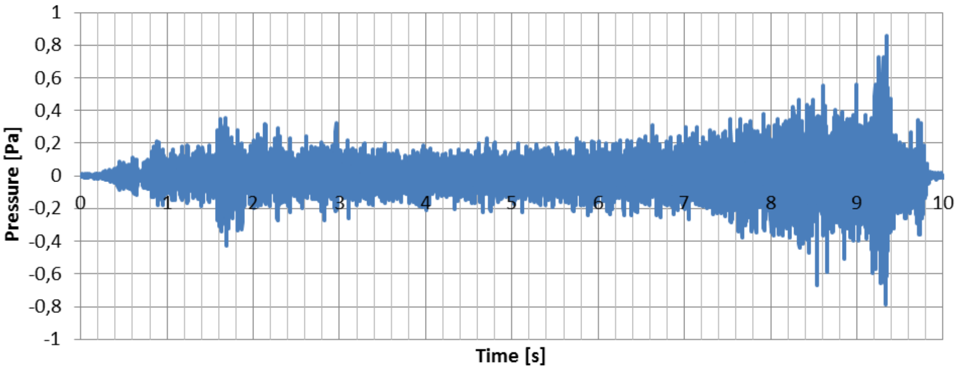


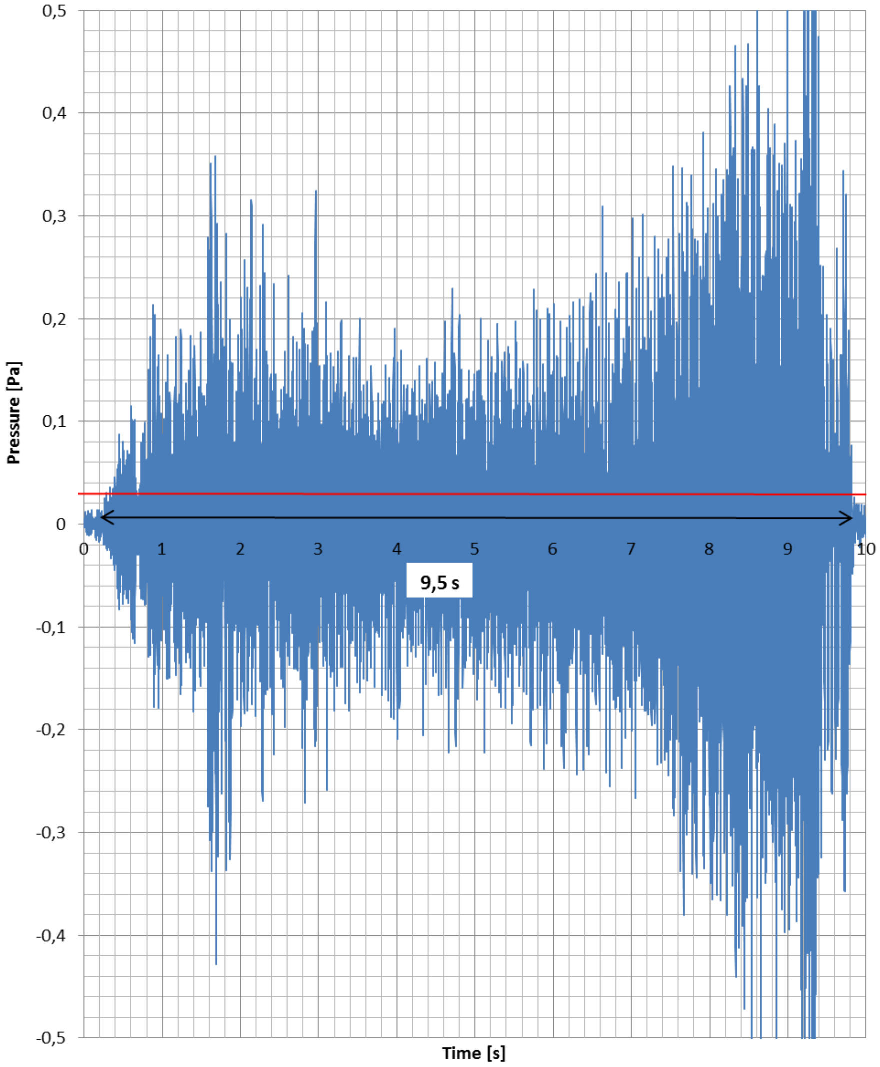
Fig. 6-27 Received time signal at 2000 km distance.



Note that the spectrum in Fig. 6-26 compares favorably with Fig. 6-14 (dotted line in Fig. 6-26). Deviations are in the order of 10 dB which can be considered good in view of the very coarse assumptions made for the result in Fig. 6-14, i.e. results are plausible. At low frequencies the predicted received level of Fig. 6-26 is lower due to the vicinitiy of the surface which lowers the observed level for distances from the surface below about ¼ wave length (Lloyds-Mirror-Effect).

Furthermore, the shallow water situation prevents sound emanating from the source at steeper angles to arrive at the receiver due to absorption on the bottom. The calculated levels in Fig. 6-26 above 200 Hz are above expectations, which is likely due to the surface channel which reduces transmission loss away from 20logr.

Fig. 6-28 Expanded view of extended signal at 2000 km distance.



The signal is 9.5 s long before it drops below background noise indicated by red line which is equivalent to 0.03 Pa.

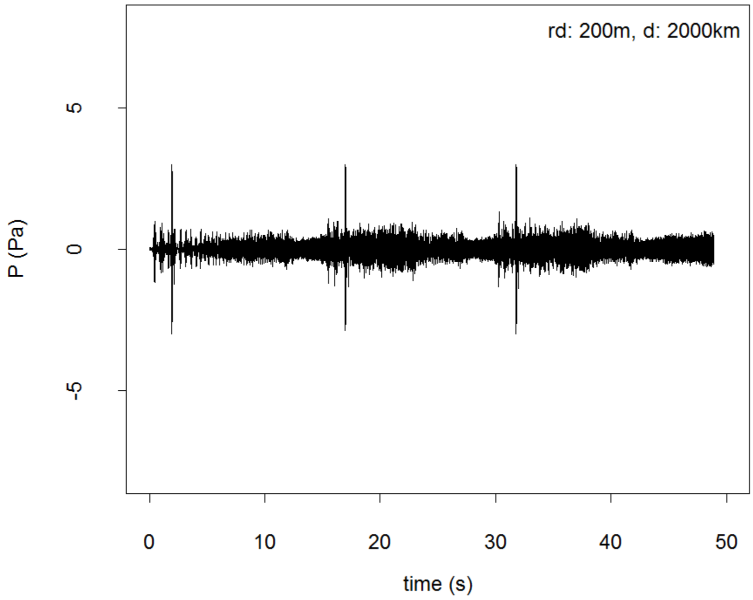
It can be seen for the shallower sites that the stretching of the received signal is not increasing linearly with distance (compare results for 1000 km with 500 and 200 km). This is a likely consequence of the combination of modal and frequency dispersion and a lower number of possible propagation paths. In the deep sites, duration and distance correlate better.

6.4 Result for multiple airgun shots

Everything shown until now was valid for one single shot. Obviously, if the stretched signal is longer in time than the shot interval of the individual received signals will overlap leading to a continuous noise floor. The shot intervals depend on various parameters of a seismic survey, but they may be considerably shorter than the results for stretched signals at large distances.

As a pure example the received time signal for an 8 G-gun array at 2000 km is overlayed representing a shot interval of 15 seconds, which merges into a continuous signal as shown in Fig. 6-29.

Fig. 6-29 Example for a time signal for a shot sequence with 15 seconds repetition rate at receiver dept 200 m in 2000 km distance, deep water conditions (4000 m depth).



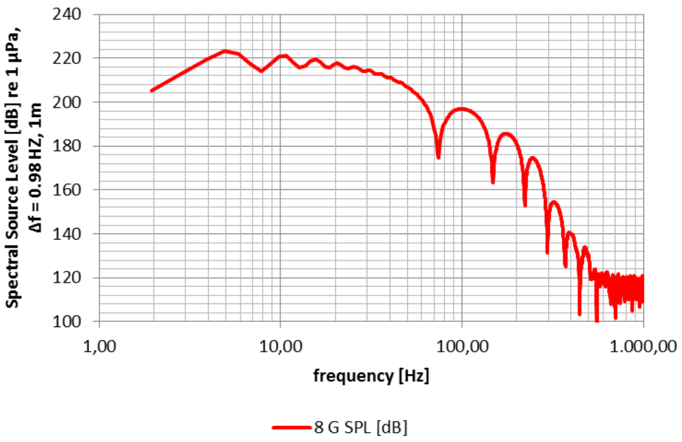
6.5 Results for higher frequencies

All calculations have been made for a frequency range of up to 300 Hz. As can be seen in Fig. 6-4, even the source level of the largest of the airgun configuration at issue is 60 to 100 dB higher than the level above 300 Hz. It is therefore justified to assume that frequencies above 300 Hz will not have an important contribution at ranges considered here. Furthermore, at 300 Hz damping becomes more and more important in seawater.

In any case, as an example, a calculation has been made including the frequency range of 300 to 1000 Hz.

Again, the 8 G-gun array is used as the sound source, its spectrum is shown up to 1000 Hz in Fig. 6-30. The range considered is 500 km, as in a larger distance the higher frequencies would have been completely attenuated by damping.

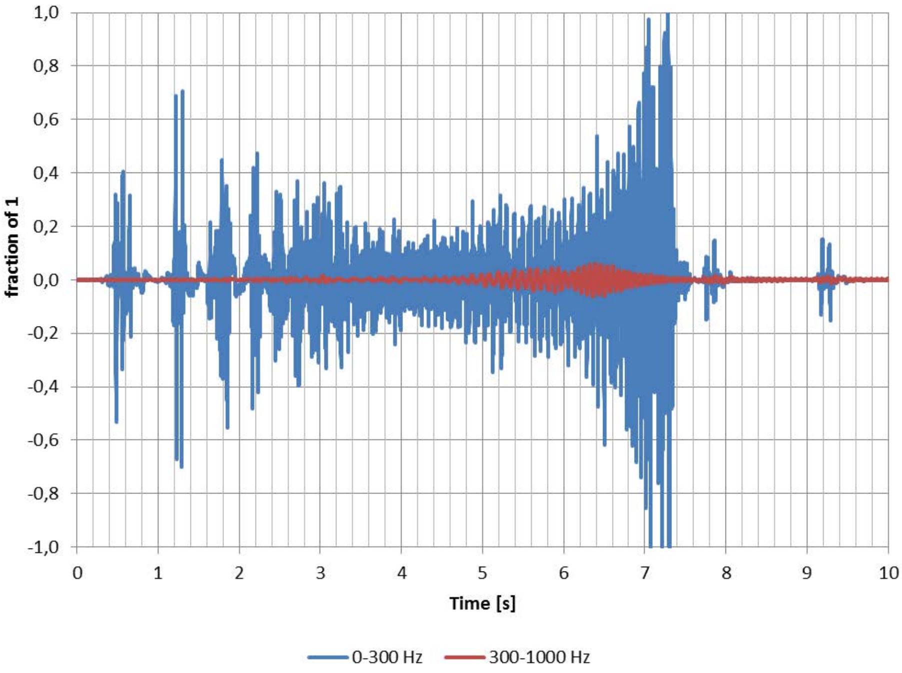
Fig. 6-30 Source spectrum of the 8 G-gun array up to 1000 Hz.



As the received time signal is almost completely unchanged to Fig. 6-21 due to the dominance of the lower frequencies, the range 0 to 300 and 300 to 1000 Hz have been displayed separately.

Fig. 6-31 shows that the high frequency contribution is low but not insignificant if no damping is assumed. Due to frequency dispersion, the maximum amplitude at frequencies above 300 Hz preceeds the maximum amplitude at low frequencies ≤ 300 Hz. Considering Fig. 6-32 the values are lower with 6 dB being about equivalent to half the pressure in the time signal.

Fig. 6-31 Relative amplitudes of the wave forms of the frequency range 0-300 and 300 to 1000 Hz.



6.6 Accuracy of modelling

The model calculations presented are made under ideal conditions, which are:

1. Range independent conditions (sound speed profile, bottom quality and bathymetry remain constant over the whole propagation range)

   It is not likely that the propagation conditions are constant over larger ranges. The consequences of this will be that more propagation paths exist which may stretch the signals further, interrupt the signal, rise and reduce levels, in all, the signal will become more irregular. By tendency more scattering will lead to lower received levels as sound waves are dispersed.

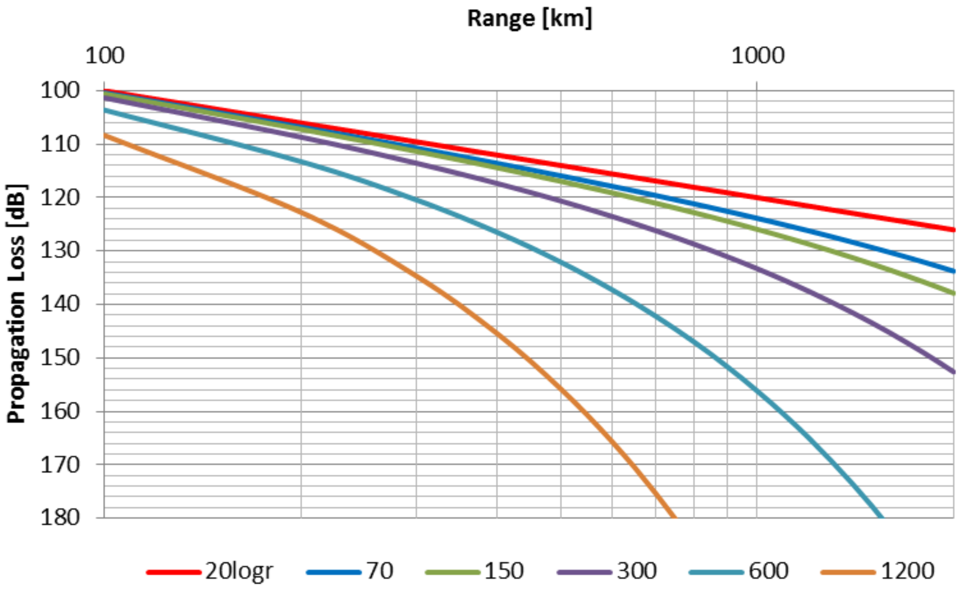
2. No damping in water

   Omission of damping (absorption in seawater) will have an effect on all frequencies after long ranges (Fig. 6-32). There are several models to describe damping with considerable differences when looking at these ranges. However the effect becomes only significant in the frequency range above 300 Hz where the airgun signals already drop rapidly in level. So if frequencies below 300 Hz are considered with the highest levels at around 100 Hz omission of damping seems justified. As a consequence, the high frequency content of the airgun shot (> 300 Hz) would not be audible relative to the lower frequencies even at smaller distances. This does not allow judgment on mammal hearing which may be more sensitive at higher frequencies. Damping will have no effect on the length of the signal as it is dominated by low frequencies.

3. No volume scattering (reverberation)

   Volume scattering is caused by the boundaries, mammals, fish, plankton, layers. It leads to echoes or a resounding noise after an impuls. It will not be important for long distance results. In closer vicinity, however, where the signal of the airguns is still short and has a high level above background noise, it may lead to extension of the signal with a certain masking effect. There is too little literature on reverberation to make a general statement on the effects. However, it may only have an effect at short distances where the received signal is shorter than the reverberation time. The expert opinion is that this distance is shorter than 100 km and will remain above background nosie for not more than a few seconds but it is not safely quantifiable.

Fig. 6-32 Damping (absorption) in seawater



Damping (absorption) in seawater according to Urik (1983). The propagation loss with and without damping for several frequencies is shown. The difference to spherical spreading (20 log (r)) marks the effect of damping.

The computer code itself is considered very accurate, i.e. if the environmental conditions are the same as calculated, results would be close to exact.

It is difficult to assess the consequences of the applied simplifications. There are no published measured time signals for very long distances available at the moment with sufficient bandwidth.

Chris Clark and Alec Duncan (personal communication) confirm however that the audible signal sounds like a sequence of irregular “blobs” with seemingly very low frequency content. This is very much what the calculated signals also sound like. Assuming that these ideal signals are partly covered by background noise from which these blobs emerge would make it even more realistic.

7 Modelling of masking

7.1 Approach of modelling masking

Most of the studies conducted in the past have focused on directly measurable masking effects of pure tones or frequency centred noise (Egan and Hake 1950; Greenwood 1971, 1972; Parker et al. 1976) as well as the relation between intensity or signal to noise ratio of the masker (Egan, 1965 Fletcher and Munson 1937) focusing on humans at first. However studies focusing on critical ratios or critical bands (Greenwood 1961) have been conducted for a number of terrestrial and Aquat Mamm, for example manatees, *Trichechus manatus latirostris* (Gaspard et al. 2012), white whales, *Delphinapterus leucas* (Erbe 2008), bottlenose dolphins, *Tursiops truncatus* (Au and Moore 1990) and some species of pinnipeds (Southall et al. 2003). While these studies have certainly led to a better understanding of how hearing processes work in different species, it is very difficult to transfer and apply these results directly to animals in the wild, because the frequency content or modulation rates of vocalisations used in the wild do not behave like a pure tone or other artificial signals used within laboratory studies. The masker itself is also in some cases an artificial signal, not necessarily similar to real underwater natural or anthropogenic background noise (with notable exception of Erbe (2008), who used real icebreaker noise).

For this reason later studies trying to evaluate the ecological impact have focused on estimating the active communication space (Brenowitz 1982; Holt et al. 2011; Lohr et al. 2003; Miller 2006) available to the animals including the possibility that animals may increase the amplitude of their vocalisations to counter increased background noise (Lombard effect, Scheifele et al. 2005).

For marine mammals calculations for estimating the reduction in active space have been proposed (Møhl 1981; Clark and Gagnon 2006; Clark et al. 2009; Gedamke and McCauley 2010; Hatch et al. 2012; Di Iorio and Clark 2009, 2010). Within this project we will focus on a similar approach employing additional signal detection algorithms to account for the zone where signals may be only partly masked due to the fact that the time stretching of the airgun signal does not cover the full time between two pulses and hence some unmasked time periods occur. In that context we aim at identifying zones where masking occurs, indepentend of it being ‘partial’ or ‘complete’ as both may have biological significant consequences.

The use of terminology in this chapter follows the guidance of the Technical Subgroup Noise of the European Marine Strategy Framework Directive (Dekeling et al. 2013)[30].

7.1.1 Methodology

To model the extent of masking we decided to use a model based on signal detection theory combined with knowledge on biological masking. The theory behind is, that detectability of a signal increases with:

- Decreasing noise (assumes constant source level of the signaling/sending animal. Essentially a detection depends on the signal to noise ratio).

---

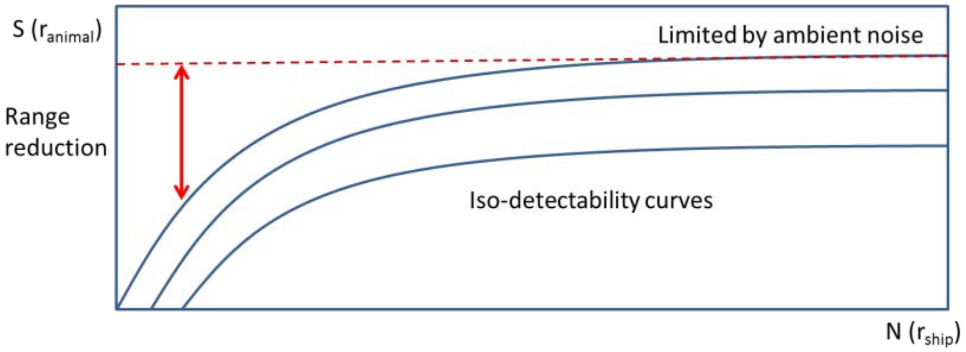
[30] The terminology used in this chapter, including reference values for source level and related parameters, follows that of the underwater noise expert group Technical Sub-Group Noise set up to advise the European Commission on the implementation of the Marine Strategy Framework Directive (Dekeling et al., 2013). The reference value for source level adopted by TSG Noise is 1 µPa m

- Decreasing percentage of time 'masked' in intermittent noise (reduction of redundancy)
- The number of trials for a repeated signal, where perception of some of the sent signals is sufficient for animals to react appropriately (also reduction in redundancy).

Hence the model is receiver centered and cannot fully account for all biological variation and differences in environmental conditions.

The central aspect of the model is a narrow-band leaky integrator combined with a simple level detector. A leaky integrator is an appropriate model for an energy detector that takes the integral over the received signal while constantly 'leaking' or losing some of the energy. There is ample evidence that such an energy detector model is an appropriate first approximation model for the mammalian ear in simple detection experiments (e.g. Green and Swets 1966) and in more general terms as a model of neuronal processing in hearing (Jennings and Colburn 2010). Hence repetition of a signal can lead to detection although not one of the signals received was perceived completely. One of the major caveats of this approach is that detectability is the criterion, while it is known, that to perceive and decode the information in a signal a higher signal to noise ratio is needed than for detection alone for most animals. Scharf (1971) however points out, that partial masking is a linear function of the loudness of the masker.

Fig. 7-1 Modelled iso-detectability curves and associated range reduction.

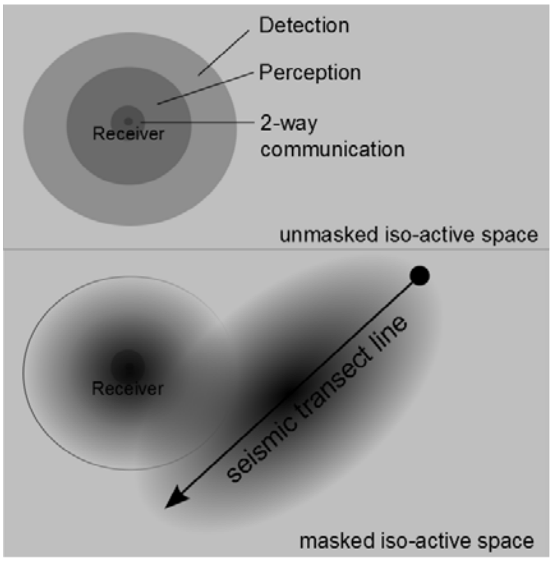


Detectability is obviously a function of the distance towards the noise source (in this case a ship, r_{ship}) which is also a proxy for the level of noise (N) emitted by the source. The signal level (S) of the animal on the other hand is the second factor involved. For baleen whales we decided to consider a fixed ambient noise level as the limit for detection (real background noise is used, with broadband sound pressure level of 80 dB re µPa).

To run the model it is necessary to band-pass filter the masker within one-third octave bands or with the bandwidth of transmitted signals. Again, there is ample evidence that a third-octave filter bank is an appropriate first approximation to the mammalian ear in simple detection experiments (Au and Moore 1990), even though the bandwidth of individual bands may not be exactly 1/3 octave in marine mammals (Lemonds et al. 2011,2012, Finneran et al. 2002). Limited information is available regarding detection of broadband signals in noise, but experiments on bottlenose dolphins suggest that when the bandwidth of the signal is larger than 1/3 octave, width of the critical band is enlarged to match that of the signal (Au and Moore 1990). The leaky integrator is then run on the masker with the time constant (TC) set to the duration of the transmitted signal alone to reduce false alarms to a level where only very low false alarm rates occur. The time constant of the leaky integrator is critical. Signal detection theory shows that the optimal time constant is identical to the signal duration, but measurements show values in the range of 30 ms to 230 ms for the time constant in bottlenose dolphins (Johnson 1968, Nachtigall et al. 2000), but may be longer for other species like baleen whales or seals. Especially for blue whales using very long signals it is then speculative to assume a longer time constant. For the blue whale calls an assumption of a matching time constant will lead to an overestimation of detectability of signals and thus most likely an underestimation of masking potential of airguns. The matching time constant has, however, been used also for the blue whale, for reasons of consistency and because this assumption simplifies modelling a great deal. To take account of this issue a second trial was set up using a time constant of 200 ms for the leaky integrator (see also chapter 7.2.1.2).

The detector is then essentially run again on a signal with a defined signal level together with the masker and detectability can be computed from the false alarm and hit rates. Iso-detectability curves can be calculated when running multiple scenarios presented in Fig. 7-1. Within these scenarios N (Noise level) can be substituted by the distance of the ship to the animal (r_{ship}) and S (Signal level) can be substituted by the distance of the animal to the source. As one major output areas of equal active acoustic communication range (iso-active space) can be computed as depicted in Fig. 7-2. Within this project we compared the output of the leaky-integrator instead of calculating detection probabilities. This is due to the fact that for calculating detection propability sufficient variability in the signals used must be given. No variability is given for airgun signals and only very small variability was found in the animal vocalisations used.

Fig. 7-2 Schematic representation of the iso-active space or iso-active areas



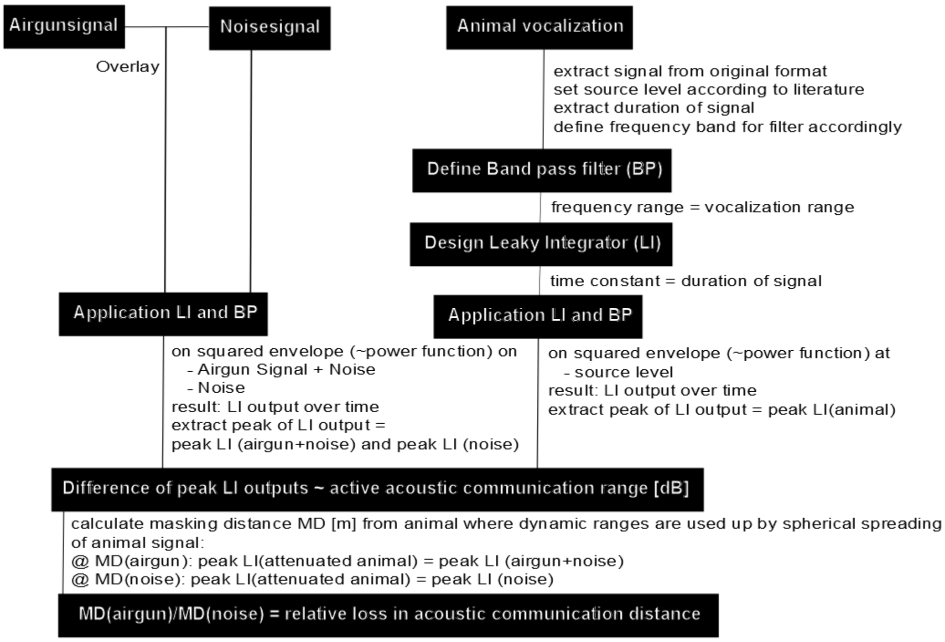
Schematic representation of the iso-active space or iso-active areas under masked and unmasked conditions. If we assume that the distance between masker and receiver is much larger than the distance between sender and receiver under masked conditions, we can reduce the problem to estimating the possible communication range under masked and unmasked conditions and calculate the loss in active acoustic communication range.

For the modelling of masking three different main scenarios regarding distance of animal and airgun were considered assuming a 15 s shot interval of the airgun pulses, which is short and may be only appropriate for smaller guns:

1. 500 km – impulses received do not overlap and cover approximately half the time available for the animal to vocalise
2. 1000 km – impulses cover nearly the whole time and stretching is different for different depths of the receiver
3. 2000 km – impulses are received as a continuous sound.

Three different receiver positions were modelled at 10, 50 and 200 m receiver depth. These depths are suitable assumptions for baleen whales, due to their mostly shallower dives, but may be too shallow for the deeper diving seals. Two different scenarios for water depth were covered, one shallow (500 m) and one deep situation (4,500 m). A schematic representation of the used MATLAB code can be found in Fig. 7-3. The chosen value of 80 dB re 1 µPa for ambient noise level is probably lower than the true ambient noise in the Southern Ocean due to the frequency spectrum of the noise used. The leaky integrator (LI) itself produces an output that can be scaled using a scaling factor. In this case we decided that an input of a continuous signal will lead to an output of the same amplitude as the input signal. Hence the LI of noise alone will produce a lower output than for instance the LI of the recorded animals signal scaled to source level. The difference of these two will be called 'headroom' from hereon, but is essentially a signal to noise ratio. This headroom changes, when the airgun is present – it is reduced, when the airgun is louder than background noise. Headroom is then essentially the acoustic communication range given either in dimensionless dB or as a linear value that the animal can use to communicate. This value can then be easily transferred using for instance assumptions on spherical spreading and absorption (in the frequency band used) into a range of natural and masked communication in kilometres.

Fig. 7-3 Scheme for modelling masking



Scheme for modelling masking in the context in different distances towards the airgun as a sound source, but also differing distances between animals (sender- receiver). This approach was converted to MATLAB-code and used on the differing vocalisations as well as the propagated airgun impulses. This schematic shows that the initial approach of calculating detectability of individual signals and masker combinations has been replaced by a simpler peak detector and comparator to define the onset of masking. A detection is defined when the leaky integrator output exceeds the level of either background noise ("natural conditions") or airgun noise ("masked conditions"). This approach only accounts for detectability of the signal and does not include perceptibility or the ability to decode the received information. Background noise was taken from real recordings and scaled to a broadband sound pressure level of 80 dB re µPa rms. LI – Leaky Integrator, MD – Masking distance, where masking distance (noise) is the natural communication range. Spherical spreading was assumed in a first step, but later replaced by a more realistic approach using spherical spreading and frequency specific absorption. Time constant was also adjusted in later trials to 200 ms.

7.1.2 Selection of model species

For the modelling purposes this study is limited to three species. Those species were agreed upon based on best knowledge of:

- Distribution and abundance of species with regard to areas that were probed using seismic airgun-arrays by the german research vessel ‘Polarstern’ during the last 20 years
- Knowledge and availability of vocalisations.
- Probable frequency overlap of vocalisations with the propagated airgun-impulses (most energy within the frequency band <300 Hz).
- Status under IUCN was considered, but not as a decision factor, as all native marine mammal species in the Southern Ocean are protected on individual level by the Antarctic Treaty.

The species group ‘Odontocetes’ (Table 7-1) was excluded from the analysis, as the frequency overlap is most probably insufficient to provide for detailed outcome of the modelling exercise. For the odontocetes it turned out, that while it is unclear at the moment whether masking occurs and is biologically significant, it is quite clear, that overlap of frequency content of the vocalisations is only marginal with frequencies of the modelled airgun impulse which suggest main energy below 300 Hz. However, when knowledge is updated, for instance for long-finned pilot whales, it would be necessary to re-evaluate this conclusion.

Table 7-1 Summary of information used for deciding the odontocete model species.

	Overlap in			Knowledge on			
Species	Space	Time	Frequency range	Vocalisations	Hearing	Abundance distribution	current IUCN status
southern bottlenose whale	Yes	Yes	border	poor	None	ok	Least concern
Arnoux‘s beaked whale	Yes	Yes	border	poor	None	poor	Data deficient
Hourglass dolphin	Yes	Yes	?	poor	proxy	poor	Least Concern
Long-finned pilot whale	No	No	Yes	poor	proxy	poor	Data deficient
Sperm whale	Yes	Yes	Yes/border	better than poor	proxy	ok	Vulnerable A1 (d)
Killer whale	Yes	Yes	Yes/border	good/proxy	ok	poor	Data deficient

For explanation: Category “Overlap” means overlap in spatial and temporal occurrence with the areas and seasons probed by seismic surveys of the Polarstern. Frequency range refers to the overlap between species vocalisation and airgun frequency spectrum. The entry “border” in this category means that the energy content of the vocalisations borders 300 Hz. Under “knowledge” we have subjectively issued the species into categories depending on whether knowledge on vocalisations/hearing/abundance and distribution is not available (None), poor, ok or good. If a proxy (knowledge on another species from the same genus) is available it is indicated as well. The current state of knowledge indicates that odontocete species with large temporal and spatial overlap with scientific airgun use in the Southern Ocean have vocalisation with main energies above 300 Hz and as such are like only affected to a limited amount by airgun masking effects at long ranges. However for long-finned pilot whales that could be affected knowledge on vocalisations is poor.

Blue whales and fin whales were selected as proxies for baleen whales in the modelling exercise of this study. For both species sufficient knowledge exists for vocalisation and high quality recordings are available. Furthermore there is sufficient overlap in frequency content as well as in distribution. In terms of IUCN status both are considered to be endangered, but in terms of abundance fin whales outnumber blue whales drastically. Hence, if significant masking occurs, an influence on individual level may be more probable for fin whales, but it could be speculated that an effect on population level might be more probable for blue whales.

However, all baleen whale species with large temporal and spatial overlap with scientific airgun use in the Southern Ocean have vocalisation with main energies below 300 Hz. Thus they all have an overlap in frequency content of their vocalisations and hence will exhibit a high potential of masking. Temporal and spatial overlap is not sufficiently given for sei whales and southern right whales, but all other baleen whales in the Southern Ocean.

Table 7-2 Summary of the information used for deciding the mysticete model species.

	Overlap in			Knowledge on			
Species	**Space**	**Time**	**Frequency range**	**Vocalisations**	**Hearing**	**Abundance / Distribution**	**current IUCN status**
Blue whale	Yes	Yes	Yes	good	noise limited	poor	Endangered A1 (abd)
Fin whale	Yes	Yes	Yes	good	noise limited	ok	Endangered A1 (abd)
Sei whale	No	No	Yes	poor	noise limited	poor	Endangered A1 (abd)
Antarctic minke whale	Yes	Yes	Yes	poor	noise limited	poor	Least Concern / Endangered
Dwarf minke whale	Yes	Yes	Yes	poor	noise limited	poor	Least Concern
Humpback whale	Yes	Yes	Yes	good	noise limited	ok	Least Concern
Southern right whale	Border	No	Yes	ok	noise limited	ok	Least Concern

For further information please look at Table 7-1. Under hearing the entry ‘noise-limited’ has the meaning that we assume, that the hearing of baleen whales is better than ambient noise at their vocalisation frequencies. We assumed that this ambient noise is characterized by Wenz curves (Wenz 1962) at sea state 3-4.

For the seal species the data availability is best for the Weddell seal and hence this species was chosen for the modelling exercise. However sufficient overlap is given as well for crabeater, leopard and Ross seals and hence future exercises should also focus on these species. Southern elephant and Antarctic fur seals mainly use vocalisations in air and may therefore be less prone to effects of masking under water in general.

Table 7-3 Summary of the information used for deciding the seal model species. NES – northern elephant seal.

	Overlap in			Knowledge on			
Species	**Space**	**Time**	**Frequency range**	**UW-Vocalisations**	**Hearing**	**Abundance distribution**	**current IUCN status**
Antarctic fur seal	No	No	In Air	-	proxy	ok	Least concern
Southern elephant seal	Partly	Yes	In Air	ok	proxy (NES)	ok	Least concern
Crabeater seal	Yes	Yes	Yes	poor	proxy	ok	Least concern
Leopard seal	Yes	Yes	Yes	poor	proxy	ok	Least concern
Ross seal	Medium	Yes	Yes	some	proxy	poor	Least concern
Weddell seal	Yes	Yes	Yes	good	proxy	ok	Least concern

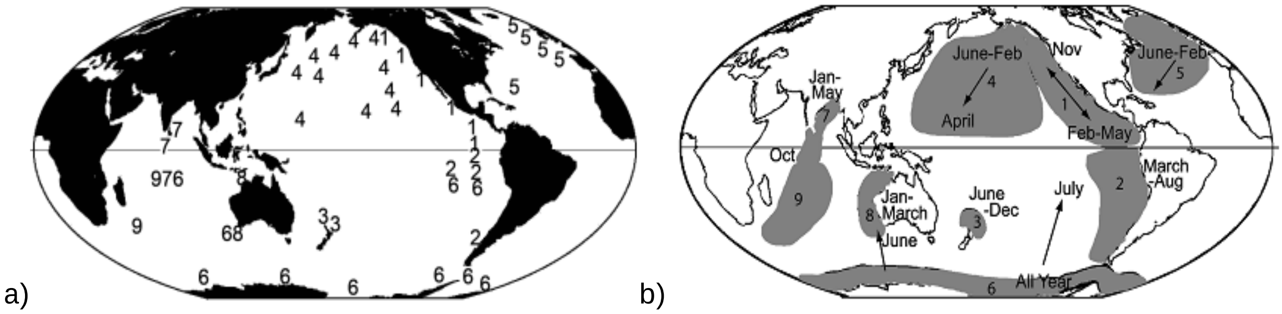
Masking modelling was hence conducted for blue and fin whales as well as Weddell seals. Vocalisations of these three species are therefore described in more detail in the next chapters.

7.1.3 Detailed vocalisations of selected species

7.1.3.1 Vocalisation Blue Whale

Blue whale vocalisations have been described in detail for most areas around the World (McDonald et al. 2006b, Fig. 7-4).

Fig. 7-4 Distribution of blue whale song and migrations and residence patterns

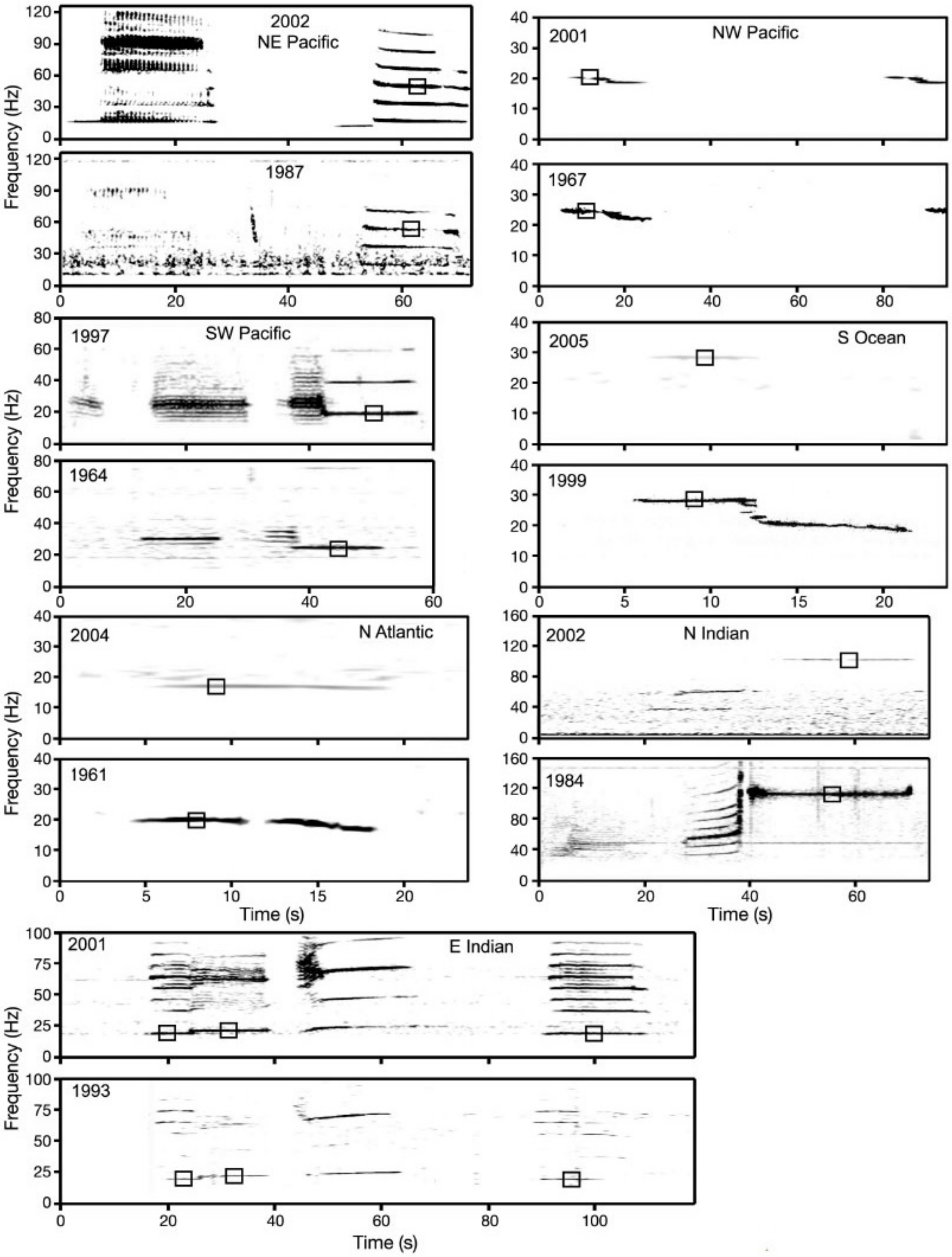


Blue Whale a) distribution of blue whale song, classified into nine regional types (numbers), b) migrations and residence patterns indicated by call type. (a and b from McDonald et al. 2006b)

For Antarctic waters the call type 6, the so called z-calls (e.g. Stafford et al. 2004) are most frequently recorded. This type of vocalisation is also recorded in the central Indian Ocean, on the south-west coast of Australia and in waters of the eastern Pacific Ocean off the coast of South America. Z-calls are recorded all year-round around Antarctica (McDonald et al. 2006b). Songs of blue whales stay remarkably constant over the years although a downward shift of 31 % in frequency was recorded for 7 of the call types known (McDonald et al. 2009, Fig. 7-5). This has been considered in our study so that recent recordings of blue whales were used in the modelling exercise. For the Southern Ocean McDonald et al. (2009) estimated the midpoint frequency shift from 1995 to 2005 to be 28.5 Hz to 26.9 Hz with similar source levels of 196.2 compared to 195.7 dB re 1 µPa m. Gavrilov et al. (2012) continued this work and estimated a slightly slower decrease in the frequency of maximum intensity (Fig. 7-6). However they did not calculate source levels.

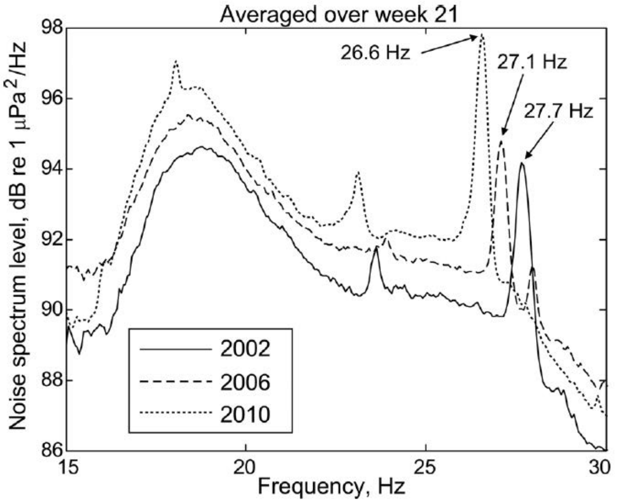
Further work on blue whale calls in the southern hemisphere was carried out by McCauley et al. (2001), but it is uncertain whether these calls recorded on the south-west coast of Australia can be used for a masking modelling exercise, as they are only partly confirmed for areas around Antarctica. Gedamke et al. (2007) found that most z-calls were registered at stations between Australia and the Antarctic continent from May to August in 2005 and 2006. Širović et al. (2004) detected blue whales year round on the Western Antarctic Peninsula on average 177 days per year with a peak in March and April and a secondary peak in October and November. Z-calls were also reported by van Opzeeland (2010) as the predominant call type year-round at the PALAOA station of the Dronning-Maud-land at the north-eastern edge of the Weddell Sea (call type A). Sea ice extent was negatively correlated with call detections of fin and blue whales, indicating a possible retreat of whales during austral winter. Density estimates derived from these recordings arrived at 0.43 calling blue whales per 1000 n mi^2, a density estimate that is about one third higher than observed during visual surveys.

Fig. 7-5 Vocalisation types of blue whales



Graph from McDonald et al. (2009b) showing vocalisation types of blue whales in different biogeographic regions of the world and highlighting (square) the temporal midpoint measurement used to demonstrate the decline in frequency.

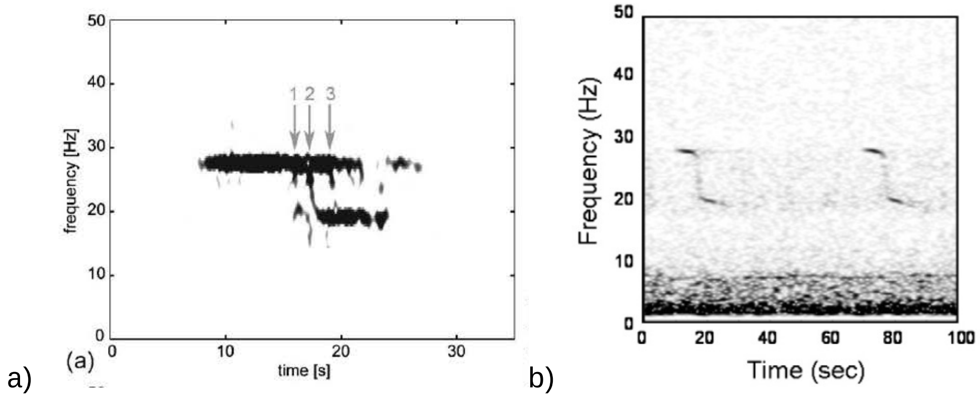
Fig. 7-6 Sea noise power spectral densities from Gavrilov et al. (2012)



Sea noise power spectral densities over a 7 day period during a time of specifically high density of blue whale z-calls. Sharp peaks indicate highest intensities and show the decline in the frequency of highest intensity.

Širović et al. (2007) calculated source levels for Antarctic blue whales around the western Antarctic Peninsula to be around 189 ± 3 dB re 1 µPa m for the frequency band with the highest energy of the signal between 25 – 29 Hz. An example of their recordings with multipath arrivals is given in Fig. 7-7a. The authors suggested that the maximum calling range for blue and fin whales could be around 1300 km. Samaran et al. (2010a) found different values for source levels of 179 ± 5 dB re 1 µPa m for recordings from the south-western Indian Ocean using a different frequency band of 17-30 Hz (Fig. 7-7b). For the modelling exercise we chose to use the 179 dB re 1µPa m value from Samaran et al. (2010a) as the blue whale calls used are from the same regions as the estimate of source level.

Fig. 7-7 Antarctic blue whale z-call



a) (from Širović et al. 2007) Spectrogram of an Antarctic blue whale call with multipath arrivals in 3000 m depth in 33 km from the animal, b) (Samaran et al. 2010b) Spectrogram of a Antarctic blue whale call (FFT 1024 points, 93.75 overlap, Hanning window). Typically the first higher frequency part contains more energy than the following lower frequency part.

Blue whale vocalisations are often repeated in regular intervals of ~64 s (Širović et al. 2004). Antarctic blue whale calls and pygmy blue whale calls are very stereotypic, so that templates can be constructed for specific detection algorithms (Samaran et al. 2008). Recordings were for instance used for occurrence (Branch 2007b; Gedamke and Robinson 2010) as well as for ecological modelling (Širović and Hildebrand 2011).

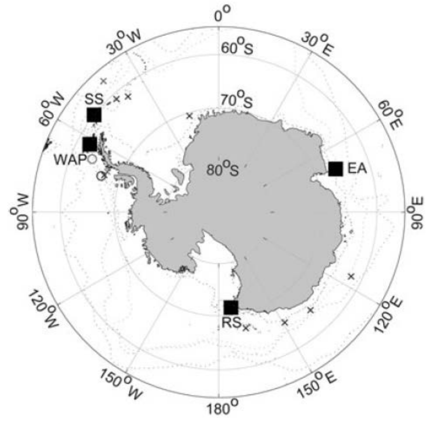
Recordings of Antarctic blue whale vocalisations were kindly provided by Flore Samaran and Ana Širović.

7.1.3.2 Vocalisation Fin Whale

For fin whales the 20 Hz pulsed vocalisation is one of the predominantly recorded sound of fin whales (see section 4.1.2). According to Croll et al. (2002) only male fin whales sing the 20 Hz pulsed vocalisations (Watkins et al. 1987) with variation between 15 and 30 Hz. Most probably the social background (for blue whales as well) is to serve as an attraction display for females. The vocalisations of fin and blue whales within that frequency range are ideal long distance communication sounds as individuals do not gather in breeding areas as other rorquals like humpback whales do, and hence long-range communication is a necessity (Croll et al. 2002). Hence a reduction in communication range can have severe effects in reproduction for fin and blue whales and accordingly has to be considered seriously for these species still in recovery from whaling.

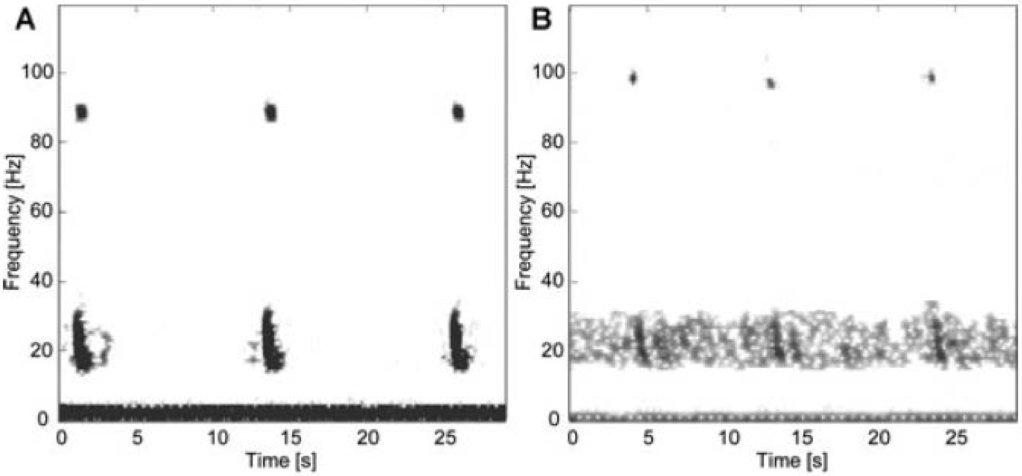
Source level measurements for these vocalisations were conducted by Weirathmueller et al. (2013) with results of 189 ± 5.8 dB re 1 µPa m. These levels are in accordance with Širovićć et al. (2007) who calculated 189 ± 4 dB re 1 µPa m source levels for fin whales around the Antarctic Peninsula. Although older literature (Charif et al. 2002) calculates lower source levels within the range of 159-184 dB re 1 µPa m correcting for surface interference we decided to use 189 dB re 1 µPa m as the reference for the modelling exercise as Širović et al. (2007) provided values directly from the area of interest.

Fig. 7-8 Permanent recording positions (black squares) used by Širović et al. (2009) to detect blue and fin whales



Fin whale calls were detected on 4 recording positions only during February to July (Širović et al. 2009, Fig. 7-8). A pronounced difference in call types were found in these recordings: calls received from the Eastern Antarctica (EA) and Western Antarctic Peninsula (WAP) had significantly different secondary peaks in the frequency spectrum than those from Scotia Sea (SS) (Fig. 7-9) suggesting two possible seperated populations. No calls were detected around the Ross Sea (RS, see Fig. 7-8). For masking modelling we have chosen a sample containing most of the energy in the 15 to 30 Hz band. However, modelling results for different vocalisations will not differ that much, as the variation in frequency spectrum is small.

Fig. 7-9 Two types of fin whale calls



The two types of fin whale calls recorded around Antarctica (from Širović et al. 2009). The difference is in the secondary peak in the frequency spectrum at ~89 Hz for Western Antarctic Peninsula/Scotia Sea and ~99 Hz for Eastern Antarctica (90 %Overlap, 500 point FFT, Hanning window.).

When considering that indeed there are two populations, one should consider, that the small energy content in the higher frequencies can be crucial for the receiver, but current knowledge does not allow for a sophisticated and founded decision on choices for modelling parameters in that respect.

20 Hz pulses of fin whales were kindly provided by Flore Samaran and Ana Širović.

7.1.3.3 Vocalisation Weddell Seal

Weddell seals use different call types. Their large acoustic repertoire has been described in detail for vocalisations in air as well as in water (Collins et al. 2005; Moors and Terhune 2004; Pahl et al. 1997; Rouget et al. 2007; Terhune and Dell'Apa 2006; Terhune et al. 1994, 2008; Thomas and Kuechle 1982; Thomas et al. 1983b).

Some of the known call types are depicted in Fig. 7-10. One vocalisation type has been attributed to Weddell seals based on similarities to other vocalisations (van Opzeeland, 2010 van Opzeeland et al. 2010). Of the vocalisations described in van Opzeeland et al. (2010) only W1, W2, W4, W6, W8, W9, W13 and W14 have considerable overlap with the spectral content of the airgun-signal in larger ranges (<300 Hz, also depicted in Fig. 7-11). However it is uncertain whether the low energy components are sufficient for perceiving the signal and its entire content. This would mean that even signals where most of the energy is received may be masked due to higher frequency signal parts with rather low energy content.

Terhune and Dell'Apa (2006) found, that a diving adult male emitted stereotyped call-type sequences potentially used for identification and as a display of dominance.

For modelling purposes we used the vocalisations T2 (associated with territorial advertisement, from nowon called W1), T9 (associated with territorial advertisement, W2), and P (associated with submission, W3) (Thomas et al. 1983b).

Fig. 7-10 Different types of Weddell seal vocalisations (from Thomas et al. 1983b)

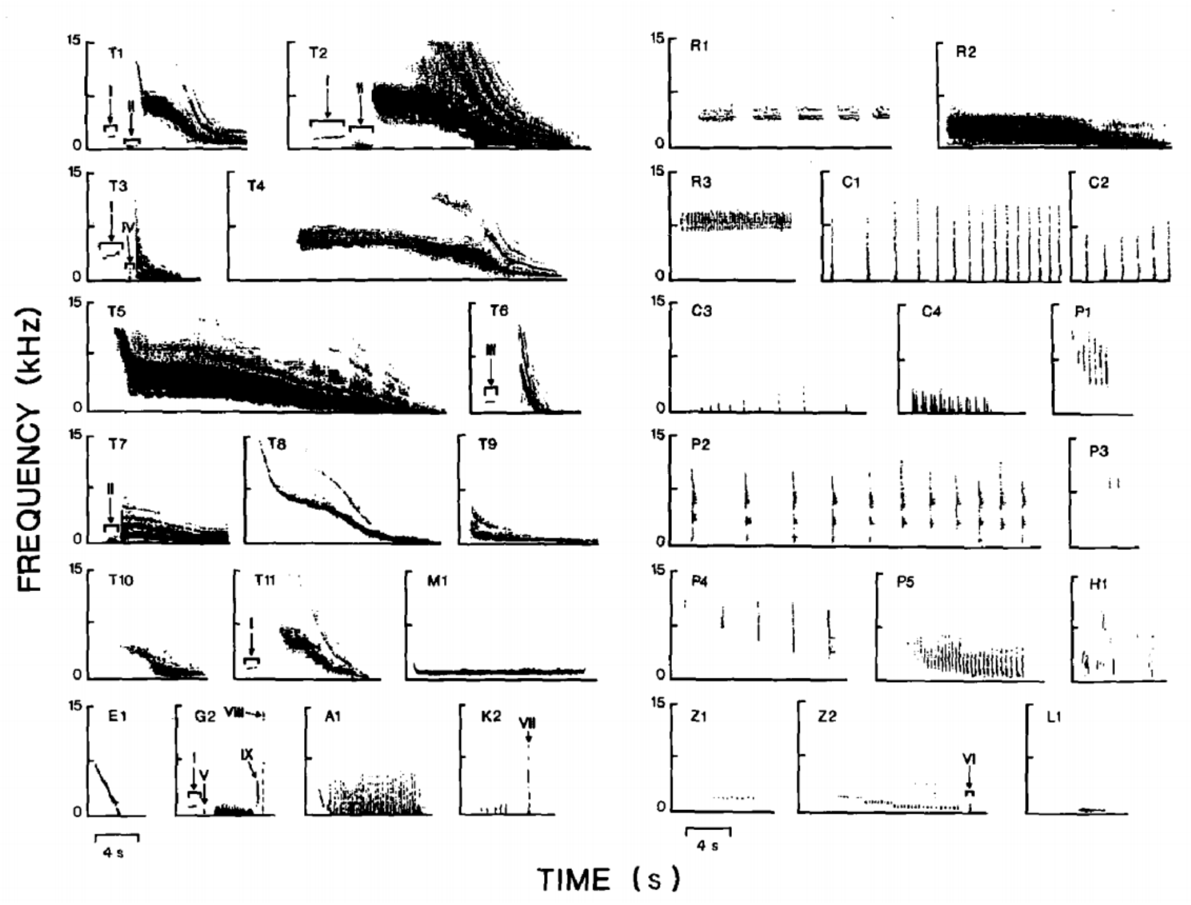


Fig. 7-11 Spectrograms of common Weddell seal vocalisations

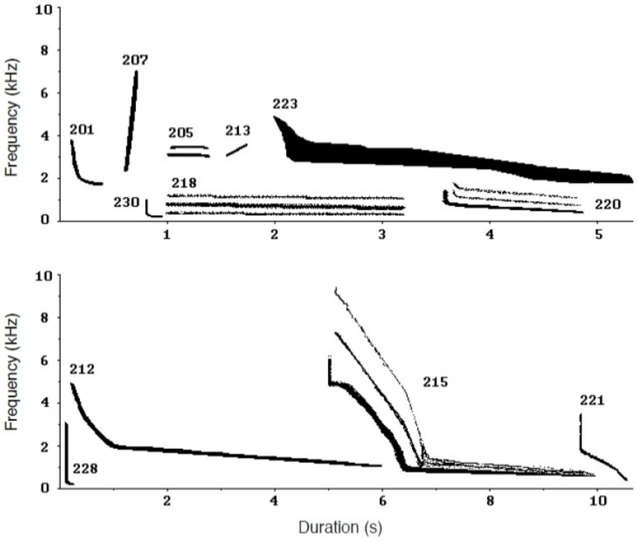


Fig. 3. Sound spectrograms of the 12 most common Weddell seal underwater call types (Group 1) at the Vestfold and Larsemann Hills. These indicate the mean frequency, duration and shape of each call type. The drawings depict the use of analysing bandwidths of 50, 110, 220 and 450 Hz at the 2, 5, 10 and 20 kHz frequency ranges respectively.

From Pahl et al. (1997). Most of those vocalisations do not have large energy content below 300 Hz.

7.2 Results of masking modelling

7.2.1 Input values

7.2.1.1 Case 1: Duration of signal as time constant of leaky integrator

The optimum case for signal detection is that the leaky integrator time constant equals the duration of the signal to be detected. We assume, that signal detection will then be ideal, resulting in the best possible signal to noise ratio. For first modelling trials the values in Table 7-4 were used. These values are based on peer-reviewed publications, except for the Weddell seals, where values published are not directly referring to the calls used within this project. The source level of 173 dB re µPa m is halfway between the maximum and minimum reported values for source level that can be reached by Weddell seals. Bandpass filters were adjusted according to the frequency range of the signal and an adjusted source level for the leaky integrator output was calculated.

Table 7-4 Input variables for the masking modelling exercise. The quantity "bandpass filtered leaky integrator equvivalent source level" is the output of the leaky integrator when the input is the product of distance and received sound pressure for a situation with spherical spreading. This quantity is needed as an input value to calculate how loud the band pass filtered sound is at the receiving animal.

	blue whale	fin whale	Weddell seal		
vocalisation	Z-call	20 Hz pulse	W1	W2	W3
source level [dB re 1µPa m]	179[1]	189[2]	173	173	173
duration = leaky integrator time constant [s]	15	1	11	5	0.25
bandpass filter upper limit [Hz]	30	25	8000	1000	2000
bandpass filter lower limit [Hz]	15	15	3000	200	100
bandpass filtered leaky integrator level source [dB]	**175.4**	**185**	**162**	**162.7**	**163**

[1] Samaran et al. (2010a)
[2] Širović et al. (2007)

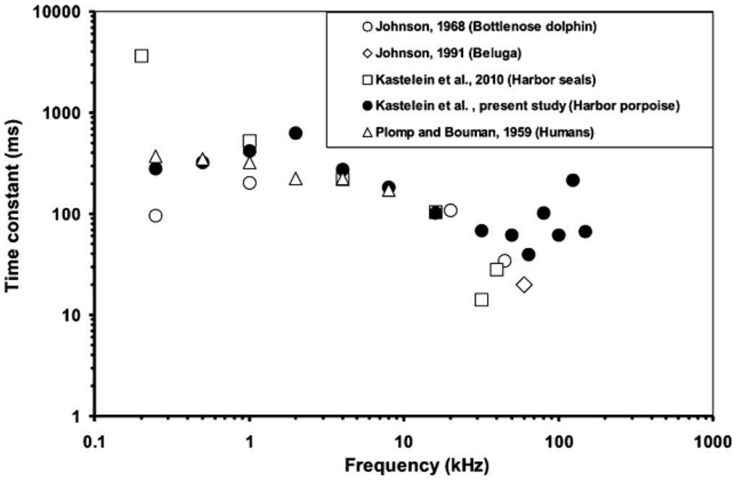
For blue whales the typical z-call was used (Fig. 7-13). The signal was recored at 42°59,91'S and 74°35,84'E in approximately 3.000 m water depth. First fin whale calls stem from the library of William Watkins (Fig. 7-14). For further simulations however, we used recordings by Ana Širović representing both – the western Antarctica and eastern Antarctica variants of the 20 Hz pulses with sufficient signal to noise ratio. For Weddell seals it was most difficult to get good quality recording due to the fact, that most recordings were made under the ice. However, we chose three examples depicted in Fig. 7-15, Fig. 7-16 and Fig. 7-17. All of those vocalisations have a broad frequency range and contain FM-sweeps. Complete modelling results are provided in appendix C.

7.2.1.2 Case 2: 200 ms as time constant of leaky integrator

During the modelling exercise it became apparent that choosing the time constant with the same length as the duration of the signal results in some cases in signal detection problems. First of all the leaky integrator and level detector are based on a band pass filtered signal and will react towards the airgun noise in the same way as towards the natural vocalisation of a conspecific. Hence the airgun is actually triggering the level detector.When the natural occurring signal has sufficient signal to noise ratio (referred to as “headroom”) the signal is not masked. When a vocalisation of amplitude, equal to the receiving masking sound, falls into the ‘breaks’ between successive airgun impulses, the leaky integrator will only in some cases (due to different overlap) be triggered by the animals vocalisations but in other cases by the airgun signals itself.

To account for this problem we conducted a second simulation assuming a time constant of 200 ms, which may be more realistic for baleen whales and large seal species (see Kastelein et al. 2010, Fig. 7-12).

Fig. 7-12 Time constants for mammals at different frequencies



(from Kastelein et al. 2010). Variation is given between ~3.500 ms down to ~15 ms. Generally in the lower frequency range (< 10.000 Hz) time constants are > 100 ms. 200 ms hence seems an appropriate assumption for the time constant of signal processing in marine mammals.

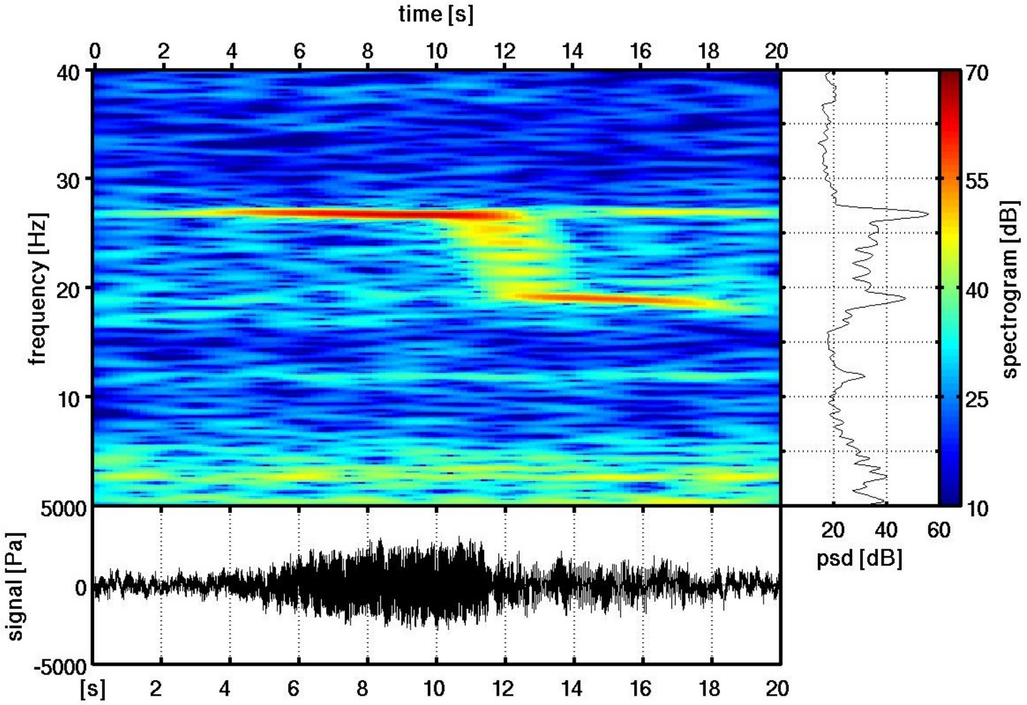
Furthermore two differerent band pass filters were applied to the Weddell seal “type 2” vocalisation to account for the large bandwidth of the input signal (Table 7-5). Signal 2a represents the whole frequency range were energy is present, while 2b represents the frequency range of highest energy, thereby accounting for audibility either of the whole signal, or of the signal with highest energy content not overlapping with the airgun frequency content.

Table 7-5 Input variables for the masking modelling exercise with the leaky-integrator time constant set to 200 ms

	blue whale	fin whale	Weddell seal			
vocalisation	**Z-call**	**20 Hz pulse**	**W1**	**W2a**	**W2b**	**W3**
source level [dB re 1µPa m]	179[1]	189[2]	173	173	173	173
leaky integrator time constant [s]	0.2	0.2	0.2	0.2	0.2	0.2
bandpass filter upper limit [Hz]	30	25	8000	1000	1000	2000
bandpass filter lower limit [Hz]	15	15	3000	200	450	100
bandpass filtered leaky integrator level from source [dB]	**187**	**191.2**	**176.7**	**175.5**	**175.4**	**167.3**

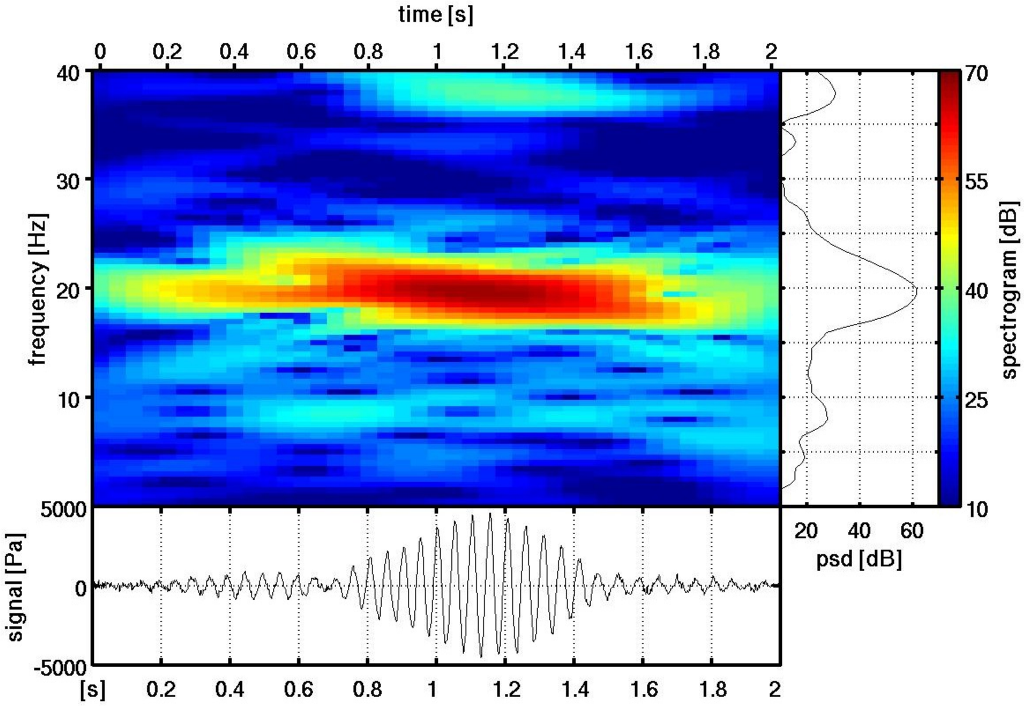
[1] Samaran et al. (2010a)
[2] Širović et al. (2007)

Fig. 7-13 Blue whale call



Blue whale call recorded in the southern Indian Ocean as used for masking trials. The signal was repeated and send through the leaky integrator and level detector. psd – power spectral density.

Fig. 7-14 One pulse of a fin whale calling sequence



The signal was repeated and masking modelling was conducted using the leaky integrator and level detector. psd – power spectral density.

Fig. 7-15 Weddell seal vocalisation type 1, T2 in Thomas et al. 1983b.

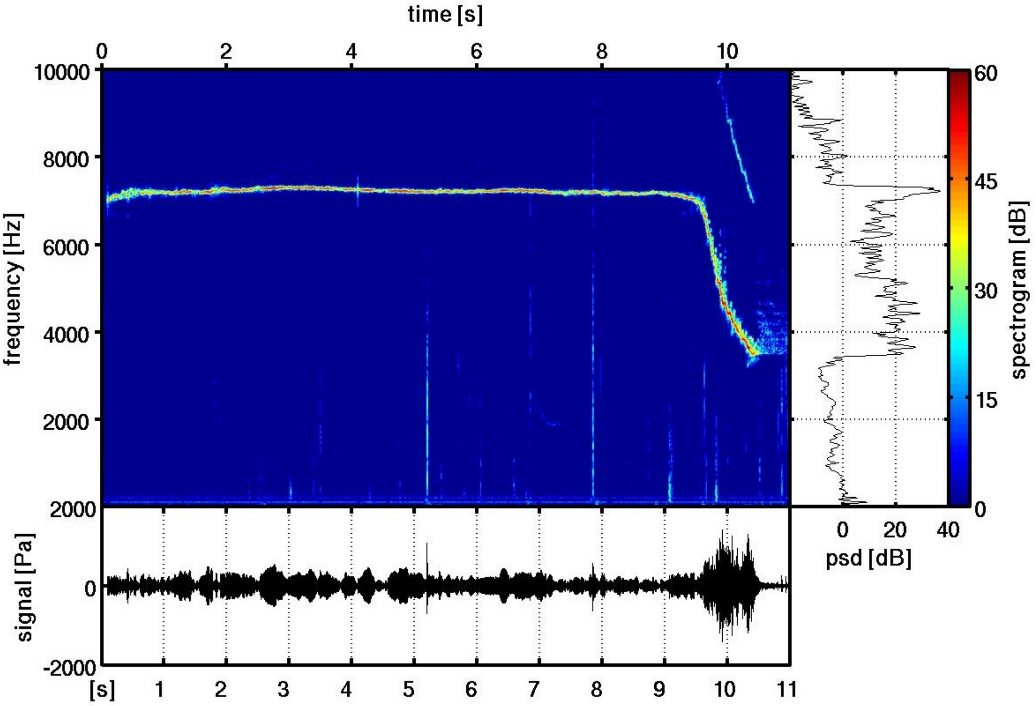


Fig. 7-16 Weddell seal vocalisation type 2, T9 in Thomas et al. 1983b.

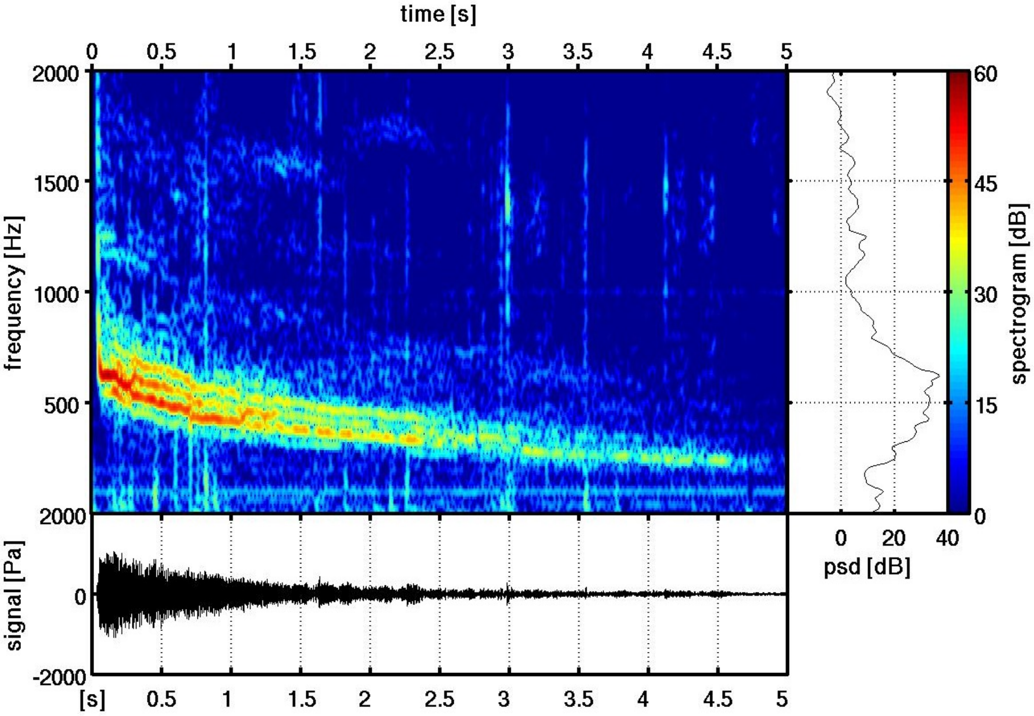
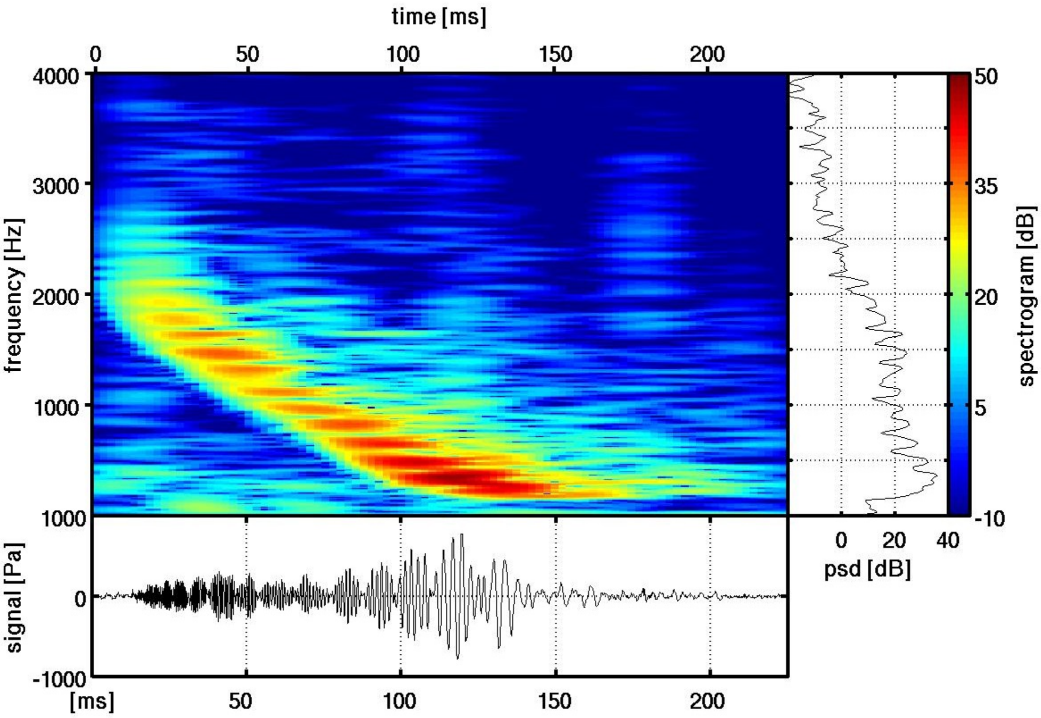


Fig. 7-17 Weddell seal vocalisation type 3, one chirp of P5 in Thomas et al. 1983b.



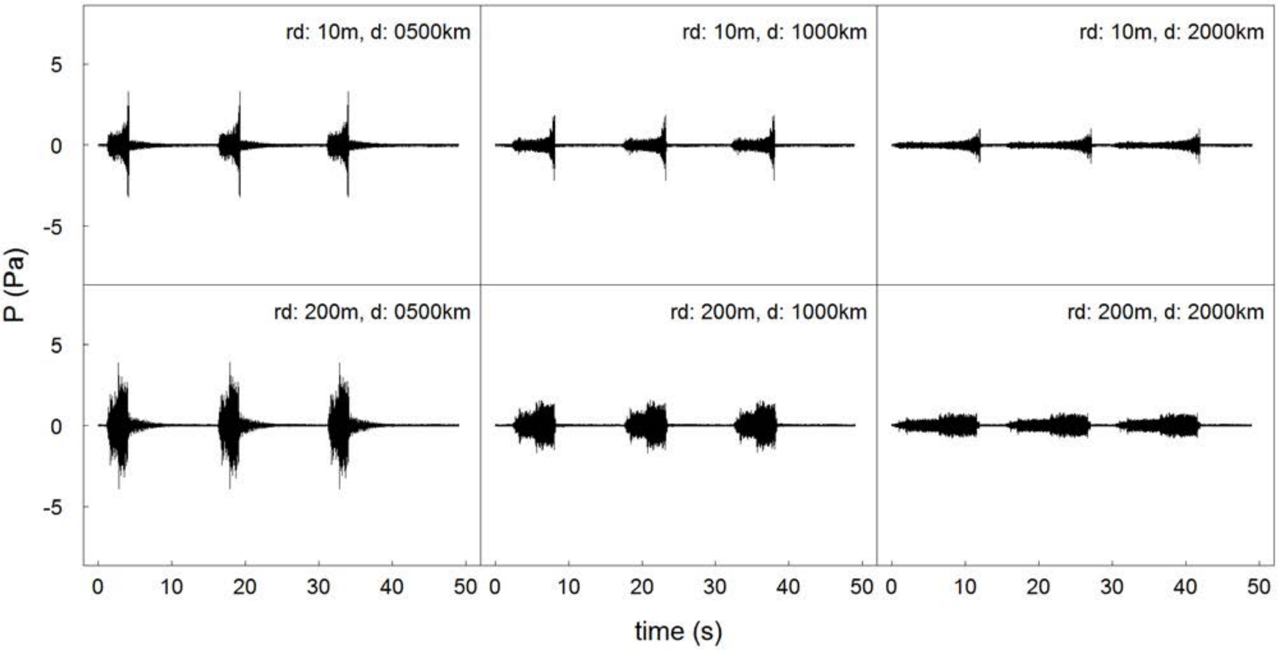
7.2.1.3 Results of sound propagation modelling used as input for masking calculations

We chose different results of the sound propagation modelling as input for the masking modelling. These are depicted in Fig. 7-18 and Fig. 7-19 for shallow areas and in Fig. 7-20 and Fig. 7-21 for deep areas. While it is obvious that the predicted pressure time signals show a reduction in received amplitudes, the peaks of the time signal may be even louder in larger distances as can be seen for the deep areas. Only three receiver depth (10, 50 and 200 m) were considered to keep calculations at a reasonable level.

In more general terms: in shallow areas the loudest part of the signal is predicted to be at the end of the received airgun signal, while in deeper areas single received pulses dominate except for very large distances, where signal stretching leads to an overlap between two airgun pulses seperated by 15 s shot interval.

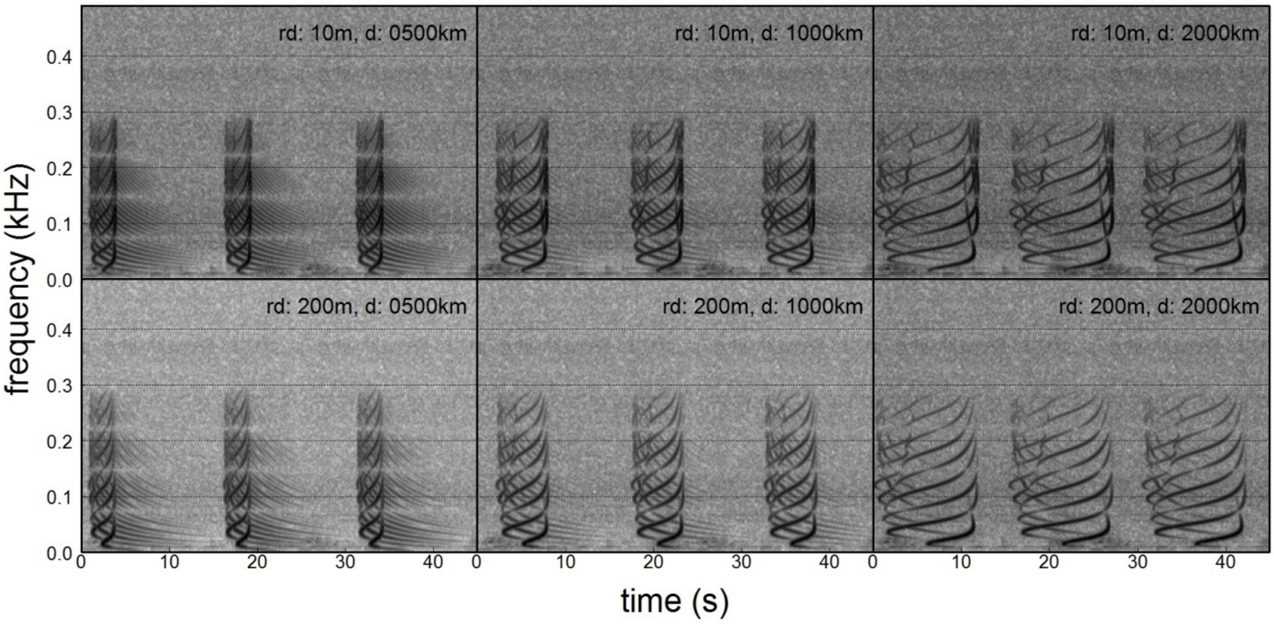
In the shallow models the reduction in received pressure is more obvious. None of the received signals shows a complete overlap with the following airgun impulse. Spectrograms of both deep as well as shallow impulses show some frequencies, that are extinguished. This may be due to the influence of Lloyd's mirror effect. However signals show very strong low frequency components with most of the energy below 150 Hz and gradually less energy towards 300 Hz. All calculation for masking were carried out on an airgun array consisting of 8-G gun as the potentially furthest reaching source at issue.

Fig. 7-18 Input Signals (estimated airgun sound pressure vs time) for the masking modelling for shallow areas (500 m Depth)



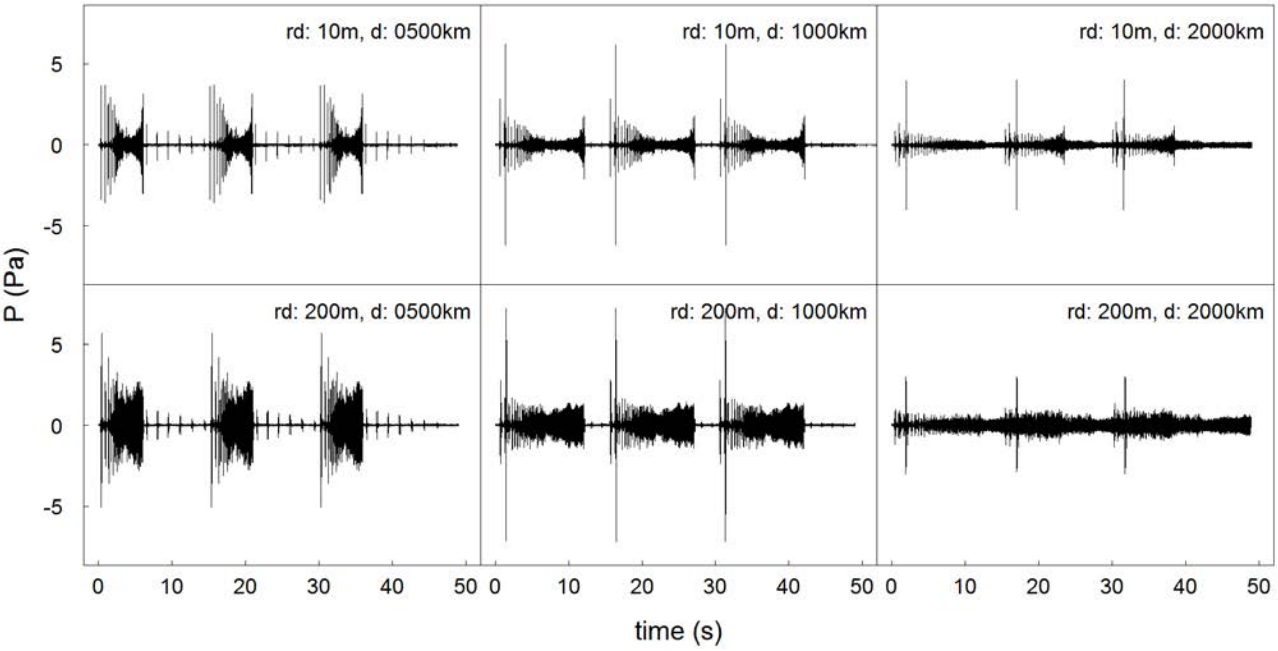
rd: receiver depth, d: distance of modelled impulse from airgun (8-G gun array). Three impulses are shown to demonstrate how the beginning and ending of sequence would look like. Only the middle impulse was duplicated and used for further calculations.

Fig. 7-19 Spectrograms of input signals (airgun) for the masking modelling for shallow areas (500 m Depth)



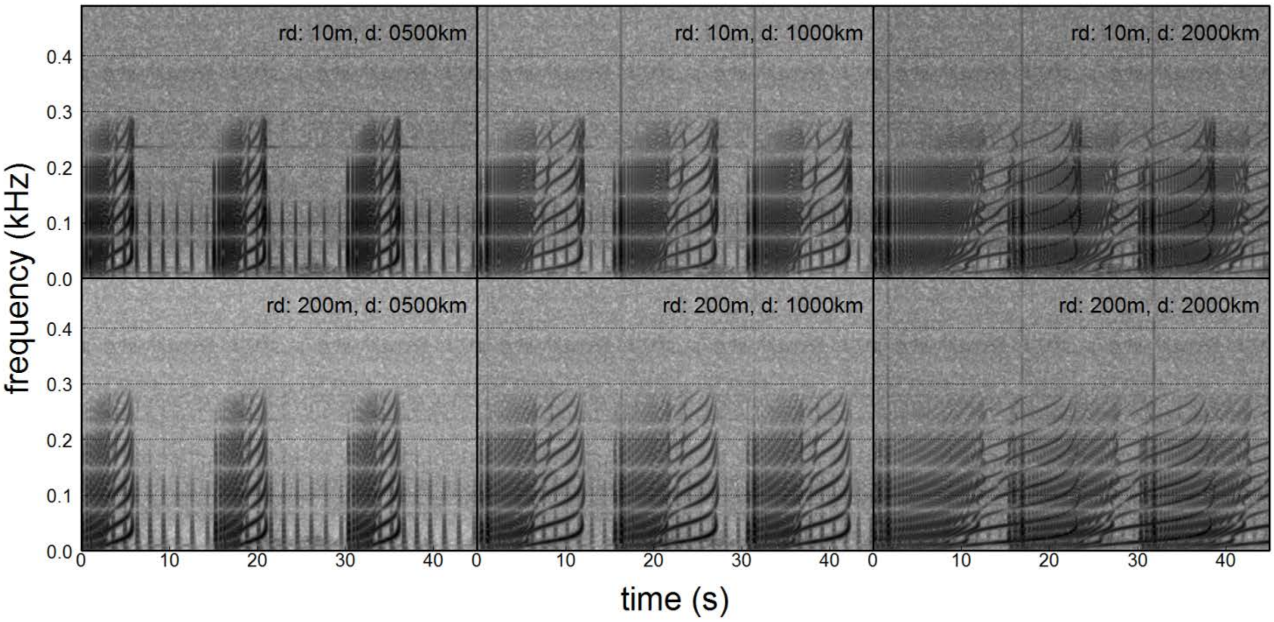
rd: receiver depth, d: distance of modelled impulse from airgun (8-G gun array with 8,5 l volume for each airgun). Three impulses are shown to demonstrate how the beginning and ending of sequence would look like. Only the middle impulse was duplicated and used for further calculations. The spectrograms show that signals have tonal frequency content and hence a broadband measure is not sufficient for masking calculations.

Fig. 7-20 Input Signals (estimated airgun sound pressure vs time) for the masking modelling for deep areas (4000 m Depth)



rd: receiver depth, d: distance of modelled impulse from airgun, 8-G gun array. Three impulses are shown to demonstrate how the beginning and ending of sequence would look like. Only the middle impulse was duplicated and used for further calculations.

Fig. 7-21 Spectrograms of input signals (airgun) for the masking modelling for deep areas (4000 m Depth)



rd: receiver depth, d: distance of modelled impulse from airgun, 8-G gun array. Three impulses are shown to demonstrate how the beginning and ending of sequence would look like. Only the middle impulse was duplicated and used for further calculations. The spectrograms show that signals have tonal frequency content and hence a broadband measure is not sufficient for masking calculations.

7.2.2 Output of leaky integrator for blue whales

Figures as for the example in Fig. 7-22 show the output of the leaky integrator over time. The animals signal is detected when the leaky integrator output reaches either the level of the leaky integrator output of background noise or of the airgun received signal. The examples shown in this and the next chapter are intended for methodological explanation for blue and fin whales. Graphs of Weddell seals do not add information and are hence omitted here.

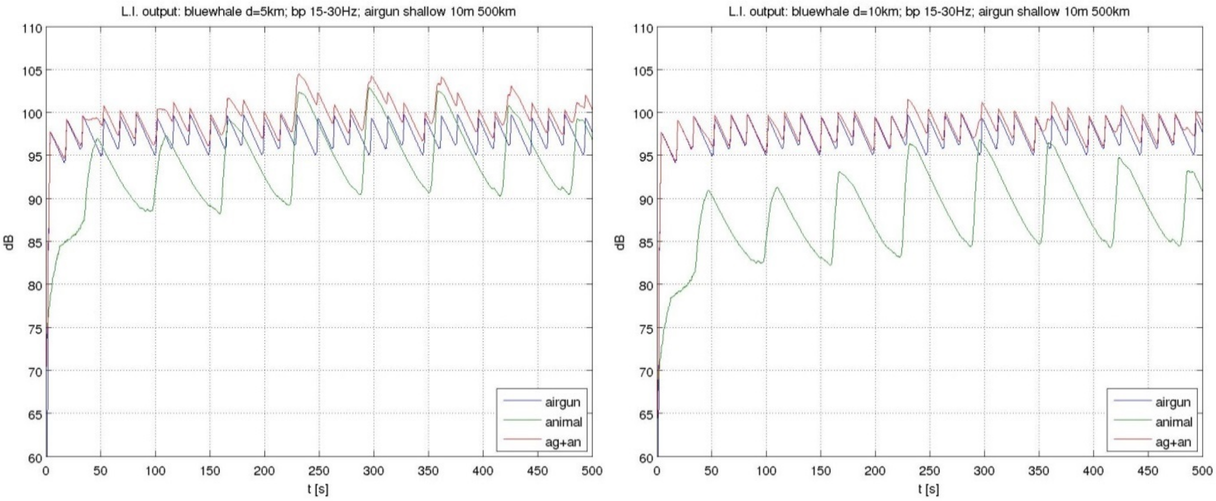
The example for the output of a leaky integrator and level detector in Fig. 7-22 highlights that in larger distances between sender and receiver (right part of the figure, distance between animals 10 km) the leaky integrator output is completely dominated by the airgun signal. Hence the blue and red curve matches each other with a few exceptions.

In the left part of the figure the distance of sender and receiver is reduced: hence the level of the animals signal is increased. The leaky integrator shows peaks that are caused by the overlay of blue whale communication with the airgun signal.

These pictures change drastically with varying distance of animals between each other, but also with the distance of a receiving animal from the airgun due to the varying input functions for the propagated airgun signal.

One has to be aware, that this representation shows only a small bandwidth of the perceived signal of the airgun. Noise with a large bandwidth and large amplitudes like airgun signals in far distance may have an effect on neighbouring frequencies according to a critical bandwidth in these species frequency discrimination abilities.

Fig. 7-22 Output of the leaky integrator and level detector for blue whales;

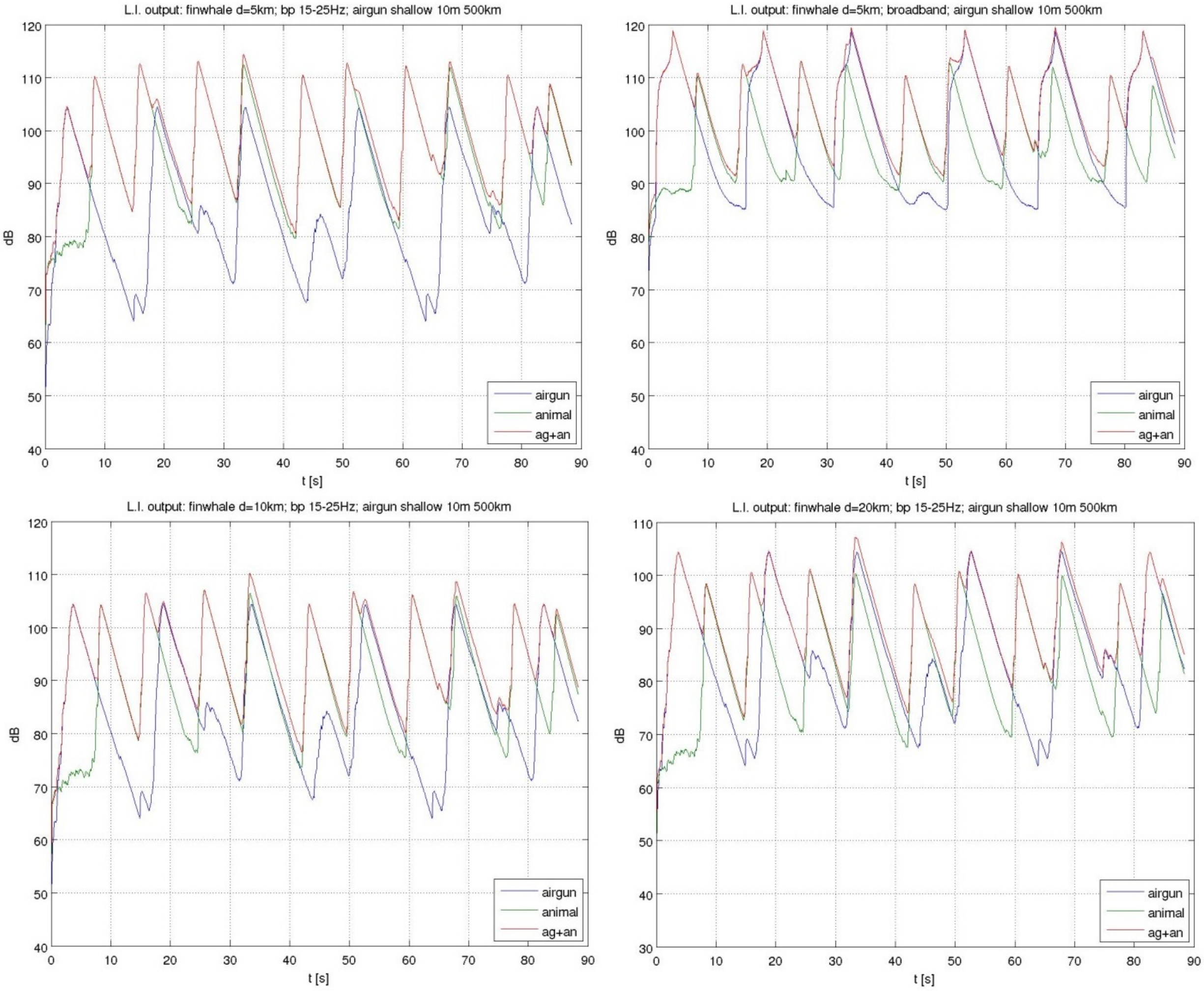


Left: output of the LI and level detector (blue line – airgun + ambient noise, green – only vocalizing animal (unmasked conditions), red – airgun + ambient noise + animal vocalisation (masked conditions)) for **5 km distance** between a vocalizing blue whale and a receiver stationed at 10 m below the surface in shallow areas (~500 m) and 500 km distance to the airgun. **Right**: same as left, but **10 km distance** between sender and receiver. It is assumed that the airgun fires in 15 seconds shot interval and that the animal repeats vocalisations over time in a natural repetition rate of approximately 50 s. For all communications (also for seal calls) a repetition of the signal was assumed according to values given in the literature.

7.2.4 Output of leaky integrator for fin whales

An example for the output of the leaky integrator for fin whales is given in Fig. 7-23. The upper two graphs compare the same situation with the input signals bandpass filtered to the frequency range of the fin whale's pulse at the left, while the right hand side shows a situation when a band pass filter is not applied. While the left side shows that detections occur and are (in some cases) caused by the fin whale vocalisations, the right side is dominated by the airgun signal and does not show a possible detection of the fin whale vocalisations. We do assume that the ear of baleen whales can generally be tuned like a 1/3 octave band filter (Payne and Guinee 1983) and hence leaving the frequency content out of the equation would lead to distorted results. The examples are intended to underline, that modelling of masking is frequency specific and hence the filtering process is essential. We used a bandpass filter fitted to the frequency content of the used vocalisation, but a matched filter would most probably provide better detection performance.

Fig. 7-23 Output of the leaky integrator and level detector for fin whales



Upper-left: output of the LI and level detector for 5 km distance between a vocalizing fin whale and a receiver stationed at 10 m below the surface in shallow areas (~500 m water depth) and 500 km distance to the airgun. **Upper-right:** same as left, but not filtered in the frequency range of the vocalisation. Lower-left: Same as upper-left, but 10 km distance between sender and receiver. **Lower-right**: Same as **Upper-right**, but 20 km between sender and receiver.

A matched filter would increase the signal to noise ratio (explained in Clark et al. (2009)). Within the time frame of this project we did neither commence matched filter analysis nor a correction of the detection threshold as proposed by Clark et al. (2009). However the matched filter would lead to a gain in signal to noise ratio of approximately 10 dB for fin whales, 12 dB for blue whales and much higher values for Weddell seals due the higher bandwidth of the signal when we assume that the signal gain equals the dB value of the time bandwidth product (Clark et al. 2009). The detection threshold that was assumed at 10 dB in Clark et al. (2009) would counteract the signal gain, so that very similar results as given here are likely when the methodology would have been applied in this project. The two lower graphs show that detectability of the vocalisation is decreasing with a decreasing received level of the vocalisation and hence also decreases with distance of sender and receiver.

7.2.5 Results of masking modelling

As expected signals with high overlap in frequency range with the propagated airgun impulse show the highest potential for masking due to reduced headroom (level of signal minus either level of background noise or level of masker) for acoustic communication (Table 7-6). Especially for Weddell seal vocalisation W1 (type T2 from Thomas et al. 1983b, chapter 7.1.3.3) there is only a small impact on the headroom, although the estimated reduction in headroom can be as much as 18 dB in deep water with a receiver depth of 50 m in 500 km distance from the airgun.

For blue whales reduction in headroom ranges from 42 to 19 dB depending on distance to the airgun and water depth. Loss in headroom was found to decrease with distance for all vocalisations tested (except for deep conditions and a receiver depth <= 50 m), which is highly interesting as it shows that even intermittent noise has a high potential for masking when the sound levels are high enough and the signal (received vocalisation) to noise (airgun impulse + sea noise) ratio becomes unfavourable.

For fin whales reduction in headroom ranged in the same order of magnitude from 43 to 15 dB. This is not surprising as the signal range has similar frequency content. Again masking potential was higher closer to the source. Signal stretching did not lead to a complete overlap between single airgun pulses in these distances.

Weddell seals vocalisation type 1 had a loss in headroom of 18 to 3.5 dB while vocalisation 2a and 3 showed a drastic decline in headroom of 37 to 18 dB (type 2a) and 45 to 25 dB (type 3) respectively. Type 2b does not show a strong reduction with 15.4 to 8 dB reduction in headroom. Reasons for these large differences can be found in the frequency content and frequencies of highest energy content of the vocalisations and the resulting different bandpass filter settings. When adapting the filter frequency of vocalisation 2 to the region of highest energy (2b) headroom is only reduced by 15 to 8 dB. This shows well that selection of the band pass filter is crucial for the outcome of the exercise when signals of a wide bandwidth are selected.

The above estimates can be considered as an estimate of the upper bound of the likely impact, because a low value of ambient noise was chosen (SPL = 80 dB re 1 µPa) and a low value for low frequency absorption has been used for the airgun signal.

Available distances for communication where determined by calculation of transmission loss via spherical spreading. The estimated loss in headroom (Table 7-6) translates into considerable losses of potential acoustic communication distances (Table 7-7) ranging from 99 % reduction for the worst case situation in blue whales (deep waters, 1000 km distance to airgun , reduction from 197.9 km natural conditions to 1.3 km masked conditions) to 89 % in the best situation. This is in the worst case a reduction by a factor 100. For fin whales the reduction is approximately 99 % (shallow water, 500 km distance to airgun, reduction from 320.8 km to 2.4 km) to 82 % translating into a reduction of acoustic communication distances of a factor ranging between 100 and 8 times less than without the masking signal. Surprisingly the acoustic communication distances for Weddell seal vocalisations 3 are reduced up to a maximum of 1.3 km and in extreme cases leave only 100 to 300 m communication distance of the calculated natural communication range of 21.6 km. Type 1 and 2b are reduced, but do not show the extreme reduction of type 3.

Table 7-6 **Potential headroom** for acoustic communications calculated using theleaky integrator (LI) and level detector, when using time constant (TC)=200 ms, seawater attenuation and assuming that 100 % free communication time is necessary for a detection.

case	Receiver Depth	Distance Airgun - Receiver	Water depth	Headroom (modelled as bandpass-filtered leaky integrator output [dB])					
				Blue whale	Fin whale	Weddell seal #1	Weddell seal #2a	Weddell seal #2b	Weddell-seal #3
1	10	500	deep	73.2	81.6	93.9	60.9	91	45.7
2	10	1000		72.8	82.3	91	64.5	85	45.2
3	10	2000		78.5	88.7	95.7	68.4	87.6	49.6
4	50	500		63.2	70.7	86.3	61.5	85.3	41.7
5	50	1000		62.6	70.6	88.9	64.9	87.2	45.4
6	50	2000		68.7	77.5	93.8	69	89.8	49
7	200	500		64.2	69.8	90.3	68.5	88.2	50.4
8	200	1000		65.5	72.4	89.8	72.5	87.3	48.4
9	200	2000		72.3	78.9	95	75.7	88	52.5
10	10	500	shallow	76.5	84.1	93.6	60.6	91.9	45.4
11	10	1000		82.5	89.8	97.6	64.1	92.3	49.5
12	10	2000		86.9	95.2	101	68.4	92.3	53.8
13	50	500		63.7	71	85.8	61.1	84.9	41.4
14	50	1000		69.5	76.9	90.1	64.7	88.2	45.2
15	50	2000		74.6	82.3	94.1	69.2	90.8	49
16	200	500		63.1	67.5	90.7	67.9	88.3	49.7
17	200	1000		69.2	73.5	96.5	74	91.2	56
18	200	2000		75.1	80.3	100.6	79.6	92.3	62
no airgun	**NA**	**NA**	**NA**	**105.9**	**110.1**	**104.5**	**97.4**	**100.3**	**86.7**

Table 7-7 **Acoustic communication distances** for the five vocalisations considered using spherical spreading as a model for sound propagation of the vocalisations, when using time constant TC=200 ms, seawater attenuation and assuming that 100 % free communication time is necessary for a detection.

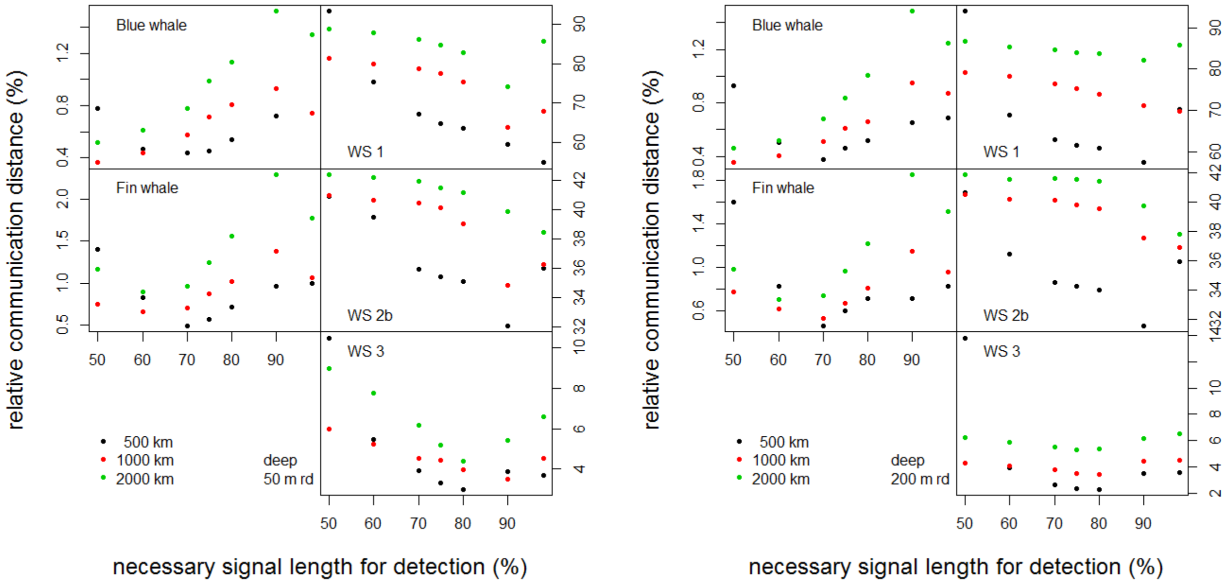
case	Receiver Depth	Distance Airgun - Receiver	Water depth	Acoustic communication distances [km]					
				Blue whale	Fin whale	Wed-dell seal #1	Wed-dell seal #2a	Wed-dell seal #2b	Wed-dell seal #3
1	10	500	deep	4.6	12.0	49.8	1.1	35.3	0.2
2	10	1000		4.4	13.1	35.5	1.7	17.7	0.2
3	10	2000		8.4	27.3	61.2	2.6	24.1	0.3
4	50	500		1.4	3.4	20.7	1.2	18.5	0.1
5	50	1000		1.3	3.4	27.9	1.8	23.0	0.2
6	50	2000		2.7	7.5	49.2	2.8	30.9	0.3
7	200	500		1.6	3.1	32.8	2.6	25.8	0.3
8	200	1000		1.9	4.1	31.0	4.2	23.1	0.3
9	200	2000		4.1	8.8	56.0	6.1	25.1	0.4
10	10	500	shallow	6.7	16.0	47.9	1.1	39.2	0.2
11	10	1000		13.4	30.9	75.5	1.6	41.0	0.3
12	10	2000		22.2	57.6	112.4	2.6	41.4	0.5
13	50	500		1.5	3.5	19.5	1.1	17.7	0.1
14	50	1000		3.0	7.0	32.0	1.7	25.6	0.2
15	50	2000		5.4	13.0	51.0	2.9	34.5	0.3
16	200	500		1.4	2.4	34.2	2.5	26.0	0.3
17	200	1000		2.9	4.7	67.2	5.0	36.1	0.6
18	200	2000		5.7	10.4	107.3	9.6	41.0	1.3
no air-gun	**NA**	**NA**	**NA**	**197.9**	**320.8**	**168.4**	**73.9**	**103.3**	**21.6**

Weddell seal vocalisation 2b shows that if the high energy above 450 Hz is considered to be sufficient for detection, ranges for communication increase drastically. Hence detailed knowledge of how the sounds are perceived prevents a better accuracy at the moment.

It is possible, that animals do not need the whole signal for detection. Hence overlap in intermittent noise is another variable and needs to be considered. We conducted a sensitivity analysis summarised in appendix C (Table 12-1 to Table 12-7), to find out whether the masking ranges of only partly overlapping intermittent noise are reduced when we assume that animals do not need the full length of the signal for detection. This sensitivity analysis varied the necessary signal length (as part of the whole signal length) for detection (as a fixed input variable) relative to the signal length of the natural vocalisation signal (Fig. 7-24). Therfore this analysis asks the question, whether the degree of masked communication ranges changes drastically (loss of communication distance) when we presume that the animals need only part of the full signal and therefore can detect signals more efficiently in intermittent noise, like received airgun impulses.

The effect is that already small amplitude fluctuations (small variations in the frequency spectrum and amplitude of the used signal) of the ambient noise used for calculations lead to an increase of the predicted natural communication range as well as the predicted masked communication range when necessary signal length for detection is reduced. The relation between those two, however, does not drastically change. Hence if we assume that animals are able to detect signals efficiently in intermittent noise it changes the effectiveness of communication in general, but does not lead to a significant reduction in the masking effect.

Fig. 7-24 Necessary signal length for a detection vs available relative communication distance (ratio between masked communication distance and natural communication distance, a relative measure for loss of communication distance). Even when the necessary signal length for a detection is varied between 50 and 100 , masking potential is changed only marginally.



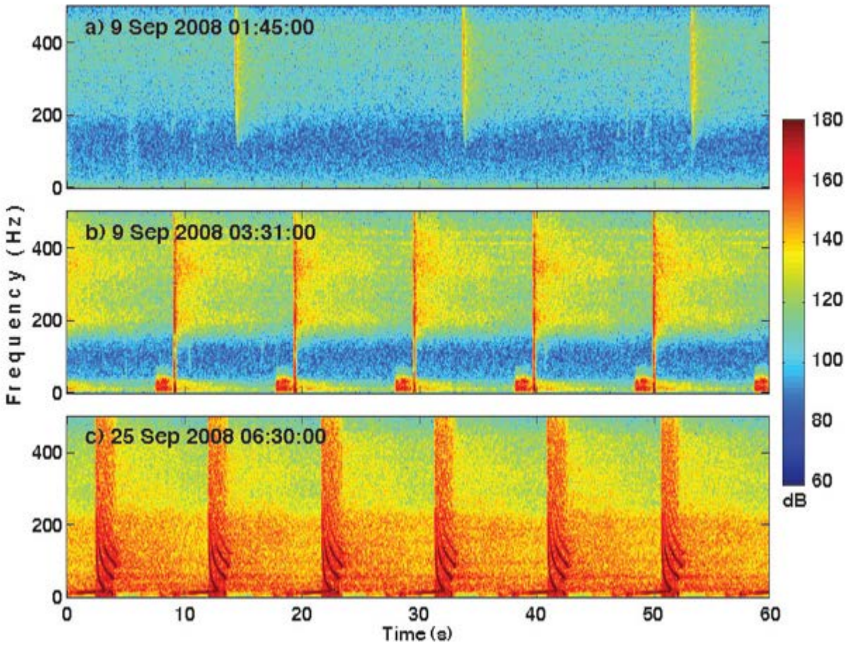
Left: For a receiver depth of **50 m**, deep sound propagation model and the tested signals. **Right**: For a receiver depth (rd) of **200 m**, deep sound propagation model and the tested signals, deep sound propagation model (4000 m water depth), WS-Weddell Seal. While masking expressed as relative available communication compared to natural communication distance decreases with distance towards the airgun array, magnitudes of potential masking are comparable although different necessary signal length for detection is assumed: Fin whales and blue whales have approximately 0.4 to 2 % of their natural communication distance, while the output drastically varies for Weddell seals depending on vocalisation type tested. The relationship is hence highly dependent on the animals' vocalisations and cannot be expressed as a simple model. Graphs for all cases can be found in Appendix C.

8 Discussion

8.1 Sound propagation modelling

Results of sound propagation modelling in the Southern Ocean show that modelled received sound levels even in 2000 km distance are above the assumed value of background noise. Thus masking potential exists even at these very large distances. However results have to be treated with caution until more measured data of airgun noise south of 60°S in the necessary receiver depth with sufficient bandwidth exists to evaluate how accurate the sound propagation model predicts the transmission loss in these large distances. In order to achieve such data, we would propose long-term monitoring of background noise, using noise recorders simultaneously logging vocalisations of marine mammals in the low frequency range. Distances to seismic survey vessels and the array configuration have to be known to validate the modelling outcome. If large differences between model outcome and measured data become apparent the modelling approach has to be adapted and if necessary, a more sophisticated approach has to be developed. Nevertheless predicted airgun levels exceeded background noise by as much as 45 dB in the modelled range of 500 to 2000 km, indicating that even if levels decrease due to an adapted sound propagation model this is unlikely to lead to a null potential for masking. Furthermore, measurements at Ascension Island indicate that the annually averaged ambient noise at 63 Hz is increased by about 3 dB by airgun signals from distant seismic surveys (van der Schaar et al. 2013).

Fig. 8-1 Airgun impulses at different distances to the source



Lowest figure shows a full airgun array exhibiting signal stretching in 17.5 km to the source showing tonal downswept components. Original heading: "Representative spectrograms of seismic activity from the M/V Gilavar: (a) mitigation gun at 18.5 km range recorded at DASAR 1 A (the shallowest DASAR at site 1) on September 9th, 2008 at 01:45; (b) full airgun array at 6.5 km range, at DASAR 1 A on September 9th, 2008 at 03:31; (c) full airgun array at 17.5 km range at DASAR 4G (the deepest DASAR at site 4) on September 25th, 2008 at 06:30. The sub-50 Hz arrival visible before the main pulse arrival in (b) arises from a head-wave leaking from the substrate, and the frequency-modulated down-sweeps visible in (c) arise arise from the geometric dispersion of various normal mode arrivals." (from Guerra et al. 2011).

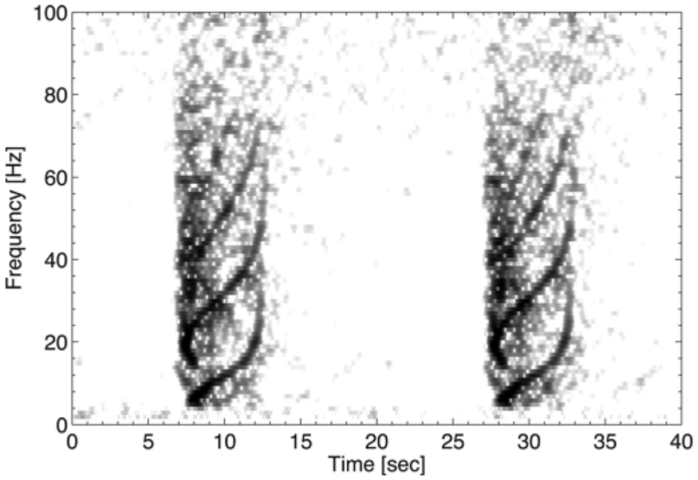
These results agree, at least partly, with the expectation of high sound levels in large distances of airgun surveys and the formation of stretched signals with possible tonal components. MacGillivray & Chapman (2006) modelled such signals and Guerra et al. (2011) recorded them in 2008. MacGillivray & Chapman (2006) however, predicted highest energy of the signal to be in frequency bands below 500-600 Hz depending on sound speed profiles in 25 m receiver depth for Queen Charlotte Basin (British Columbia, Canada) in comparison to the 300 Hz predicted in our study. Both studies predicted in agreement:

- Sound propagation effects lead to higher transmission loss in shallow areas
- In deeper areas surface ducts lead to decreased transmission loss and hence higher received levels in far distances

Consequently masking potential is higher in deep areas, but is not insignificant in shallow areas.

Spectrograms of the modelled received airgun impulse of this study furthermore show very strong similarities to airgun impulses recorded 10 m above the seafloor in the Chukchi Sea in 235 m water depth (Roth et al. 2012, Fig. 8-2), giving us confidence that the modelled frequency content is reliable and hence masking calculations are carried out using the correct frequency information. Highest frequencies depicted by Roth et al. (2012) are lower than our model outcome, but that may be due to restrictions of either the recording equipment, or due to the differences in environmental conditions that we assumed for our modelling exercise.

Fig. 8-2 Airgun shots registered in the Chukchi Sea



Airgun shots registered in the Chukchi Sea showing strong similiarities to the modelled airgun frequency content for Antarctic properties in this study. Original heading: "Modal dispersion of two airgun shots, received by the hydrophone at 10 m above the seafloor. The shots – 20 s apart – each contain four modes observed as frequency upsweeps. The modes are spread-out over more than 5 s with energy between 7 and 80 Hz (from Roth et al. 2012).

8.2 Significance of masking due to airgun impulse noise

Although a number of questions still remain (explained below) the outcome of this study shows that masking due to impulse airgun noise is highly possible and a population effect cannot be ruled out. Based on the assumptions used for our propagation and masking model (most importantly that the detetection threshold, signal gain and directivity index are zero and that the leaky integrator is an appropriate model for baleen whale and seal hearing) it is concluded:

- A model to predict potential masking by intermittent sounds has been established. This model is based on a leaky integrator and level detector combined with a simple model for sound propagation of animal vocalisations. Necessary inputs are the waveforms of the received airgun impulses and high quality recordings of the species of interest, background noise and the necessary proportion of unobstructed communication time for a detection. Considerung the range of communication loss depending on the chosen vocalisation and species we would at the moment not recommend to extrapolate from these findings to other species, which were not modelled within this project. For the modelled species we can conclude that for blue and fin whales loss in communication range is most probably severe and may have an impact on population level. For the highly vocally active Weddell seals modelling of all known vocalisations would be necessary to conclude on potential population level effects of airgun based masking effects.
- We did not commence a population level model as as uncertainties within sound propagation modelling for these large distances are high. Modelling results must now be ground truthed by recordings with sub-sea-noise hydrophones and reliable distance estimates between receiver and surveying seismic vessels. Most available data originates from bottom mounted hydrophones, but baleen whales as the likely most affected suborder of cetacean, move mostly in the upper water column of up to ~200 m depth and do not commence deep dives. Hence data from bottom mounted recorders are of limited value to estimate the effects on baleen whales. It is further observed in practice that measured sound transmission loss tends to be higher than predicted with numerical models such as used in this study due to anomalous low frequency absorption in the sea. The cause of this low frequency absorption is unknown (Kibblewhite & Hampton, 1980). This difference will increase with distance.
- Masking potential is highest for low frequencies below 300 Hz. This leaves baleen whales and Antarctic seal species as the probably most affected species. Vocalisations and other relevant signals for biota with highest energy content above 300 Hz are most likely not or only little affected, thus odontocetes are most likely less affected in general.
- Masking potential is higher for sound propagation in deeper areas. Hence animals may be affected in large distances when they are south of 60°S even if seismic survey vessels are operating north of 60°S.
- Masking potential can be high even at distances, where signal stretching does not lead to a prolonged received signal covering the whole airgun shot interval. Especially for long vocalisation signals like blue and fin whales masking potential is predicted to be higher at 500 km compared to 2000 km, but the magnitude communication loss is similar.
- The estimated reduction in communication distance due to the presence of airgun sounds is highest for fin whales and blue whales. As this estimated reduction is approximately two magnitudes lower than estimated communication distance without the airgun sounds, a

population level effect cannot be ruled out. However it depends strongly on when the airguns are operated (seasonal abundance, association of sounds with feeding, mating or predator avoidance etc.) and how long and how well the animals can mitigate the effect of masking (for example by redundancy in calls or increased source level). A shift in frequency is most likely not effective for blue and fin whale calls, as received airgun signals are broadband. Z-calls of blue whales are recorded year-round around Antarctica, ergo for this already depleted species numbering in the low thousands, masking may have the strongest impact due to the necessity to communicate over large distances of probably up to 1.300 km. It is likely that a theoretical communication distance overestimates communication distances necessary for the individual whale – but for an already depleted species like blue whales, necessary communication ranges are most probably already increased in comparison to natural conditions, where blue whale were more numerous. Therfore it is essential to apply the precautionary principle until further research has evaluated the actual population level impact of communication masking by the use of airguns on blue whales and other endangered Antarctic marine mammals.

- Seals are most likely less affected, but especially the low frequency, long carrying parts of their vocalisations may be masked. Mostly this does not concern the full spectrum of a sweep; hence parts of the vocalisations will be unmasked. The biological significance of this 'partial' masking will depend on whether the animals strongly depent on the low frequency part of the vocalisation for detection. The same applies for the upper frequency part of a fin whale vocalisation: If the difference between 90 and 100 Hz is important for the animals (if they for instance need the information to find the correct mating partner), then the detection of this weak signal has biological significance and is therefore crucial. Behavioural aspects like this have not been included in the modelling approach.
- The approach to use a leaky integrator as a model for detection of the received signals has provided much insight due to the possibilities to use different amount of overlap between airgun and vocalisation and the possibility to vary parameters like the time constant of integration. However, restrictions are that the leaky integrator cannot (at the moment) cope with the ability of animals to detect signals from different incidence angles with higher precision (directivity index). This ability is based on the ear to estimate a bearing towards a sound source. With increasing angle between two sound sources it is much easier to separate them. There are no data available to predict directional hearing in baleen whales and subsequently to use them as a parameter for this exercise. This caveat may be addressed in the context of controlled exposure experiments.
- Passive listening (listening to non-conspecific sources important to the animal), as well as possible masking effects of natural sources that may have a large impact as well, have not been addressed within this project. Prior et al. (2011, 2012) for instance highlighted that using long-term data sets from hydrophone stations points towards large influences of ice noise (station Cape Leuwin, Western Australia) and natural seismic activity (Juan Fernandez, Chile). These natural noises overlap in frequency content with the vocalisations of marine mammals as well and have to be considered in a population level assessment to set their possible masking effects into a relation with the additional effect of seismic airguns.
- Natural sound sources, including vocalisations from distant populations of baleen whales, may also contribute to masking, but this possibility has not been addressed within this project. Introduction of additional natural noise sources will increase the background noise

and therefore decrease the estimated communication range without airgun signals. The signal to noise ratio of animal vocalisations against such an increased background noise will decrease and lead to a decrease in loss of communication range due to the presence of airgun signals.

The results rely on the validity of the model used for the sensory hearing system, and using a different model may affect our conclusions. However it is commonly assumed, that the mammalian ear is an energy detector and hence the leaky integrator seems to be an appropriate first model as long as other, more detailed knowledge about the species considered, is not available.

The developed model of sound propagation allows for a reliable estimation of signal stretching and can be adapted to other environmental conditions. The masking model currently allows estimating loss in acoustic communication distances and (under the assumption used) indicates a high probability of masking effects up to distances of 2000 km. For the tested baleen whale vocalisations a high masking potential has been demonstrated and should be considered under the precautionary principle. Although it is tempting to conduct a population level impact assessment uncertainties in sound propagation and masking modelling are still too large and may be of a magnitude that can highly affect the outcome of a population level assessment. Prior to any population level impact assessment more data needs to be collected on received airgun signals and, if possible, hearing mechanisms and the sensory system in baleen whales and seals native to the Southern Ocean to underpin the relationships described in this study.

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10 Appendix A: Sound fields

The following plots are calculated for selected octave-mid-frequencies. The color scale is the same in all plots. Parameters for source, water body and bottom as in the text.

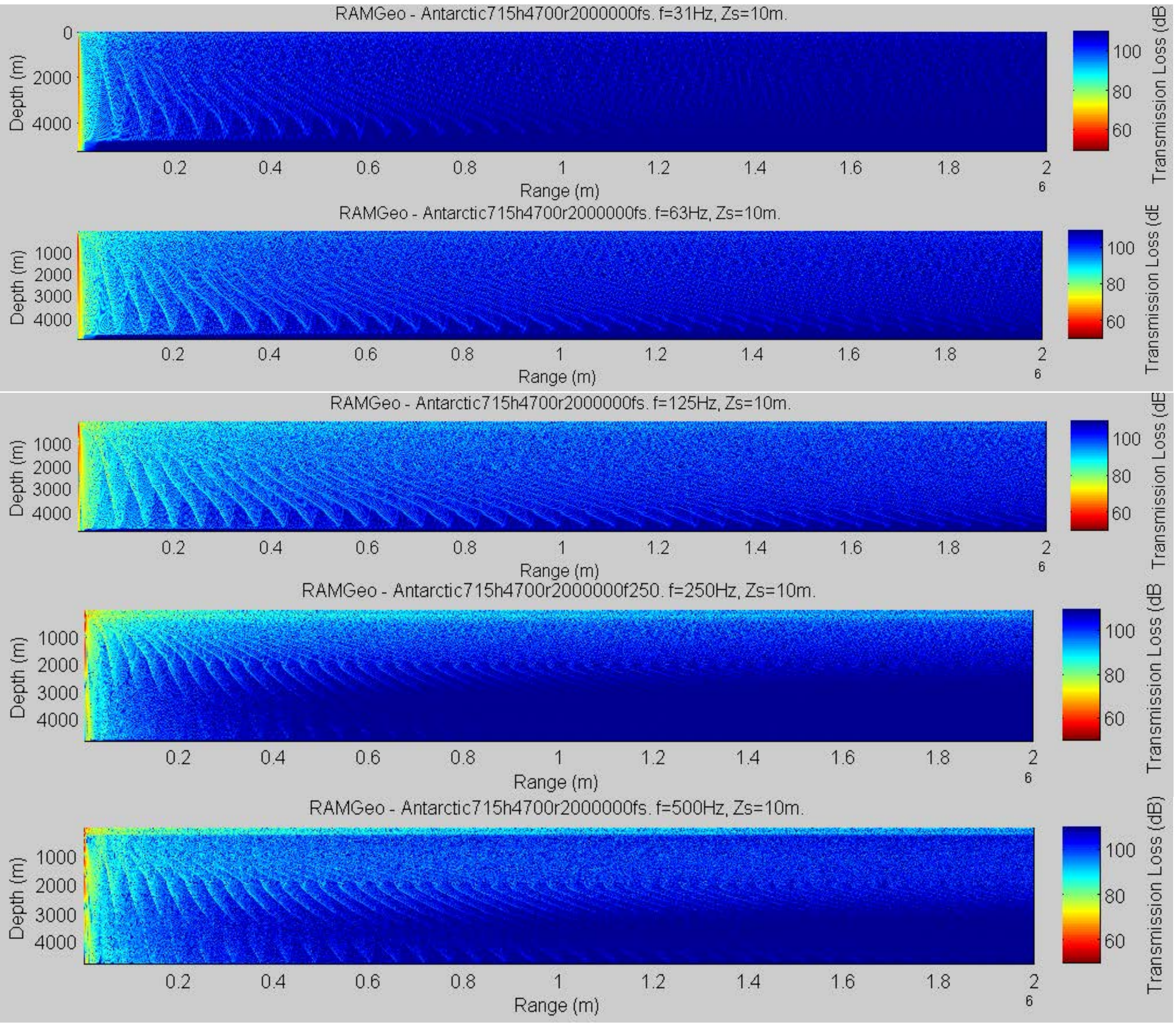
Calculations are made with the Parabolic Equation solver RAMgeo of AcTUP, all are made for 2000 km range.

Results allow a first judgment of level decay with range as a function of depth.

No damping is assumed. There is no effect from an undulated water surface.

10.1 Results for 4000 m depth

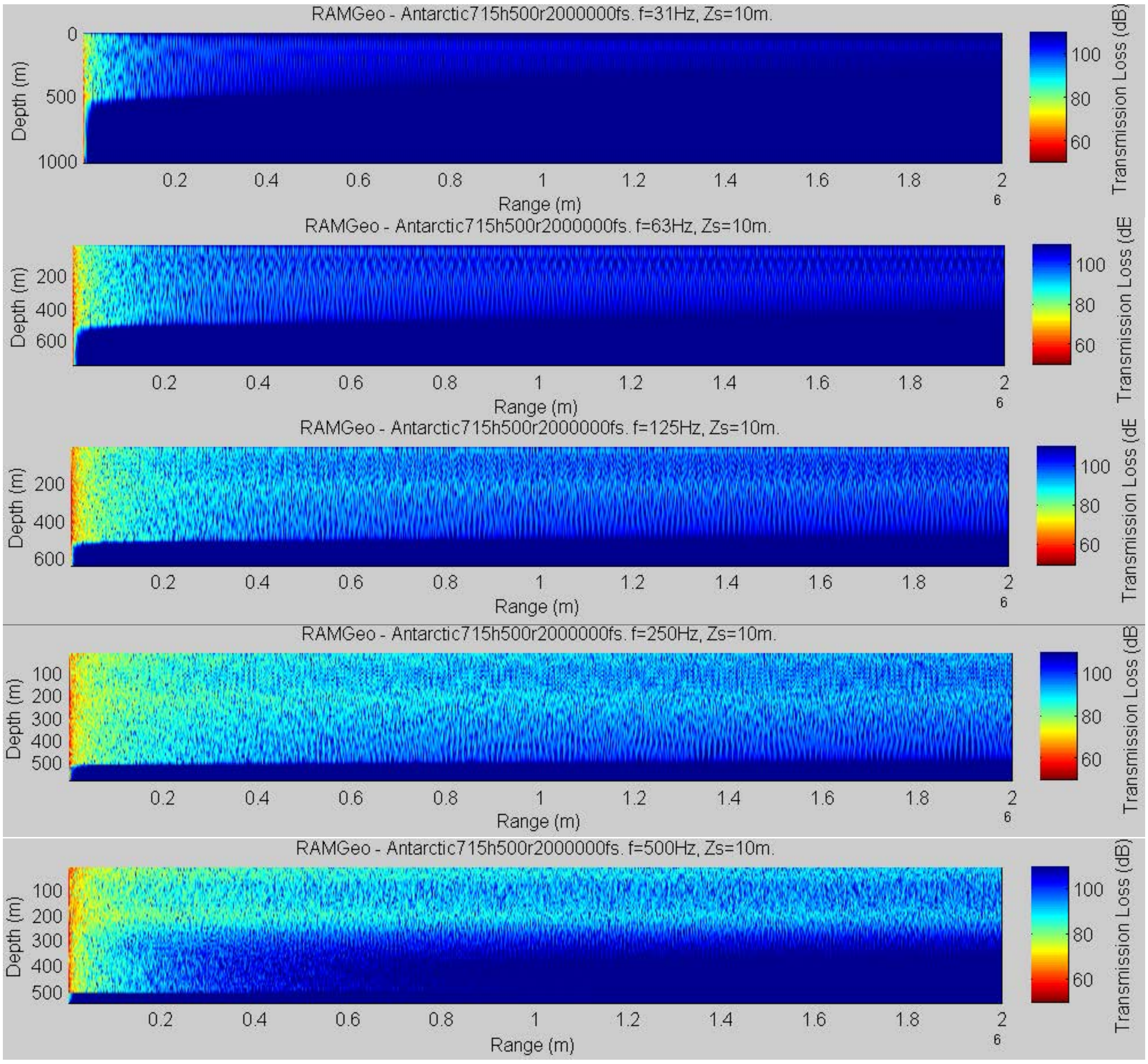
Fig. 10-1 Results of RAMGeo for different frequencies at 4000m water depth



From top to bottom: 31, 63, 125, 250, 500 Hz

10.2 Results for 500 m depth

Fig. 10-2 Results of RAMGeo for different frequencies at 500m water depth



From top to bottom: 31, 63, 125, 250, 500 Hz

11 Appendix B: The phenomenon of stretching

The sound speed in the Antarctic has a positive gradient with depth, i.e. the speed of sound increases with depth. In summer there is a small layer with a negative gradient but in essence this has only limited effect on sound propagation.

Because of this sound speed profile sound waves are refracted upwards towards the water surface. This leads to a concentration of sound energy close to the surface.

There are only a limited number of propagation paths, also called modes, between a source and a receiver. Each mode goes along with a certain vibration shape of the water body. For each of the frequencies the mode shape is a bit different which leads to the effect that high frequencies move a bit faster than low frequencies (frequency dispersion). Further, different propagation paths lead to different travel distances and different average sound speeds. For example a sound wave going very deep below the surface travels a longer distance than one close to the surface but travels most of tis distance in water with a higher sound speed than present on the surface. As a consequence this sound wave arrives early because of the high speed but with a low level because of the larger distance it travels. On the other side a wave travelling close to the surface arrives with a high level but is comparatively slow. The effect is called mode dispersion.

The longer the distance the more obvious frequency and mode dispersion become, leading to stretching of any short impulse to signal of significant length of more than 10 seconds after a distance of 2000 km.

In environment where the bottom plays a role, in our case the environment with a sandy bottom in 500 m depth, matters are more complicated because of its frequency dependent absorption behaviour. In this case stretching time may not increase proportional to distance.

11.1 Signal stretching at receivers for all configurations

The following is a complete collection of signals and spectra for all 4 airgun configurations in all 4 environments for receiver depths of 10, 50 and 200 m and for distances 100, 200, 500, 1000 and 2000 km. Emphasis is on the length of the signals for judging of masking.

Background noise was defined at 0.03 Pa in the time domain.

It is obvious that propagation will continue far beyond 2000 km but computer limits would not allow further evaluation in reasonable time.

Any effects from reverberation or damping effects are not accounted for. Normal material damping is not considered relevant for frequencies below 300 Hz.

300 Hz was taken as the upper limit because contributions from the sources were considered too low to yield meaningful results at large distances. Besides, calculation time increases rapidly with frequency.

11.2 Structure of display of results

Spectrum bandwidth is always 1/(length of time window)

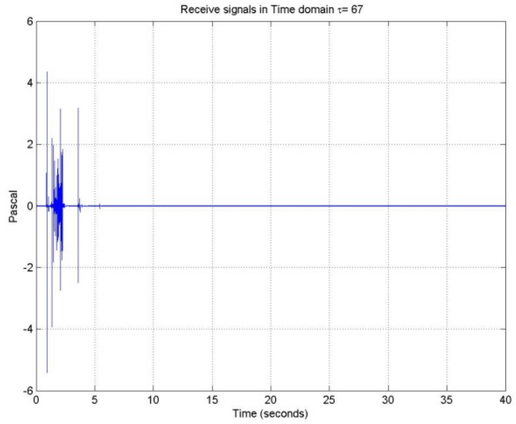
The order of display of the following figures is according to the following scheme:

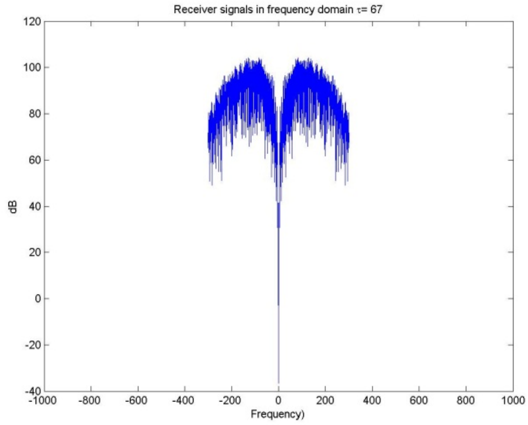
11.3 1 G-gun Array, source depth 5 m

11.3.1 Depth 4000 m

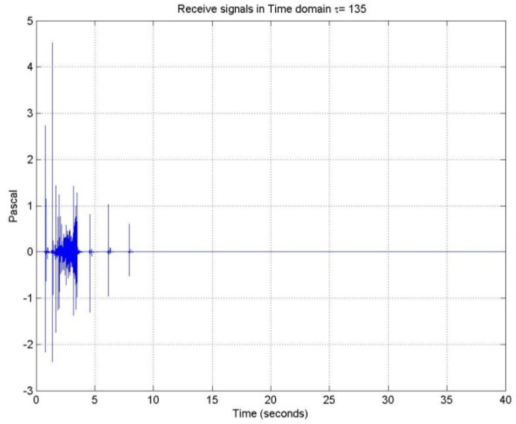
11.3.1.1 Station 715

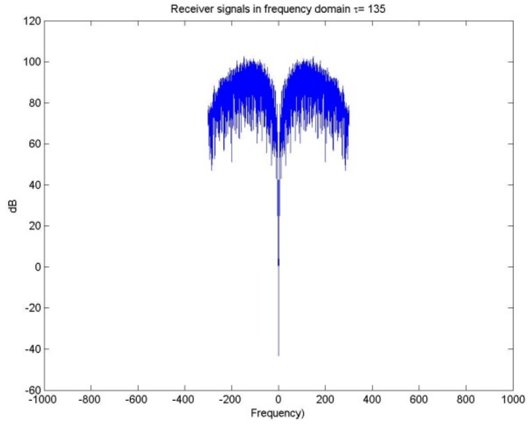
Receiver depth 10 m



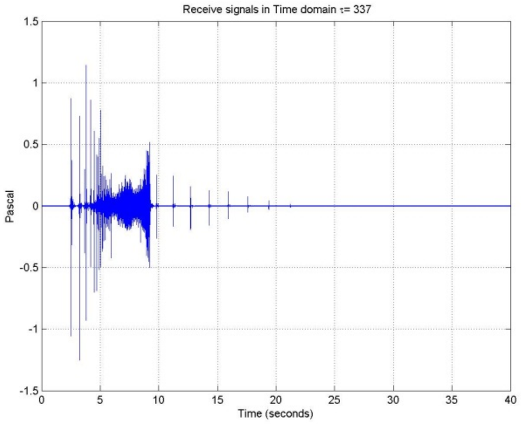


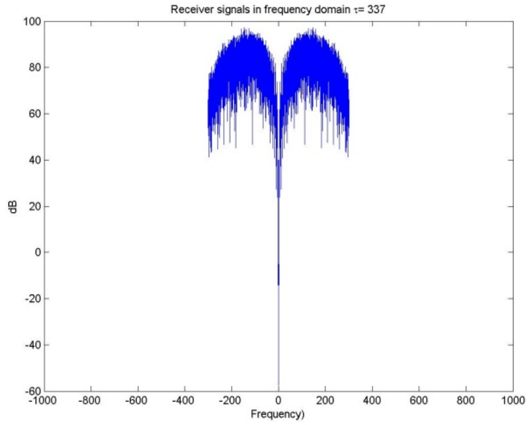
100 km



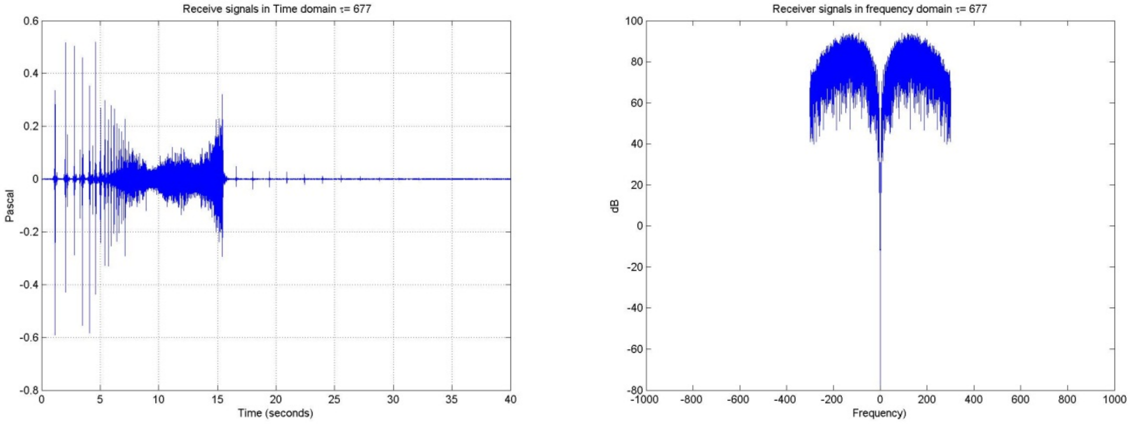


200 km

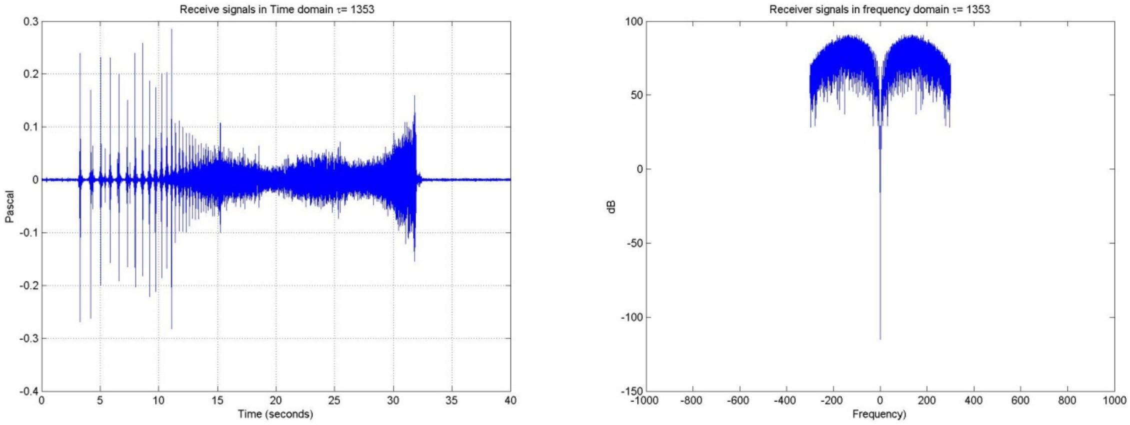




500 km

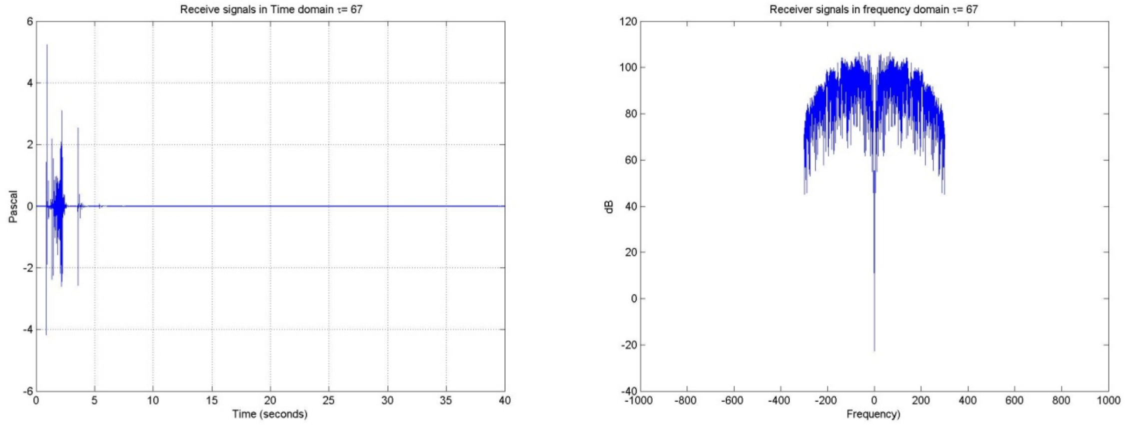


1000 km

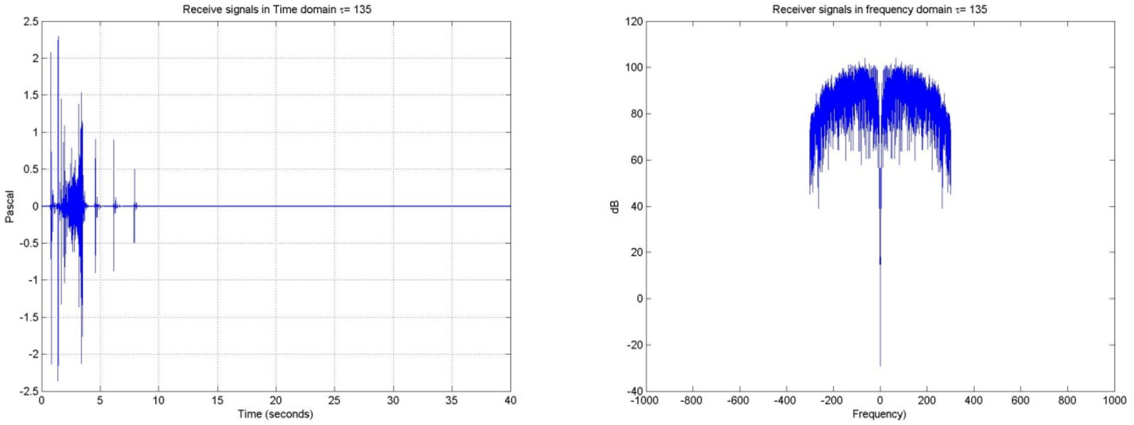


2000 km

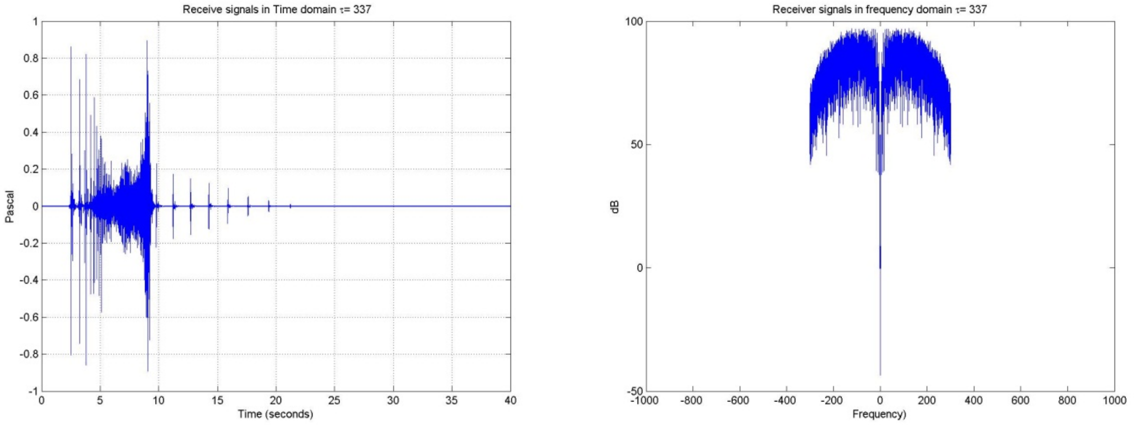
Receiver depth 50m



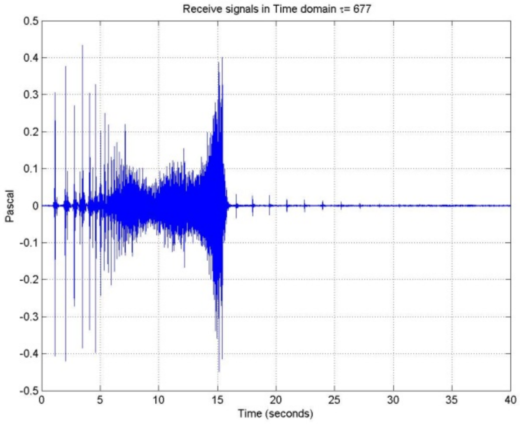
100 km

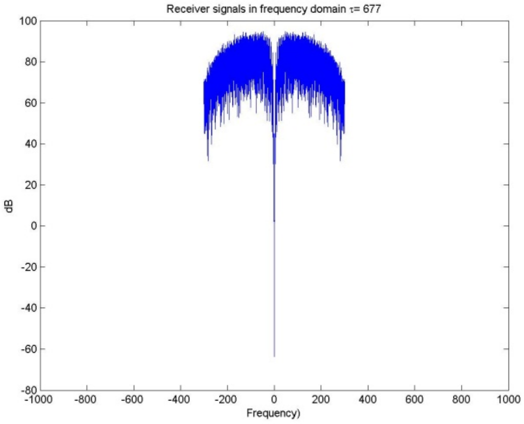


200 km

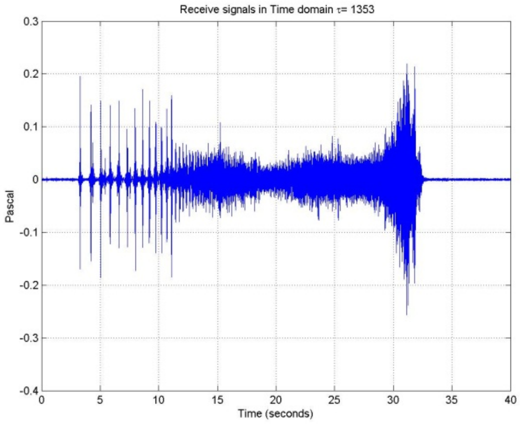


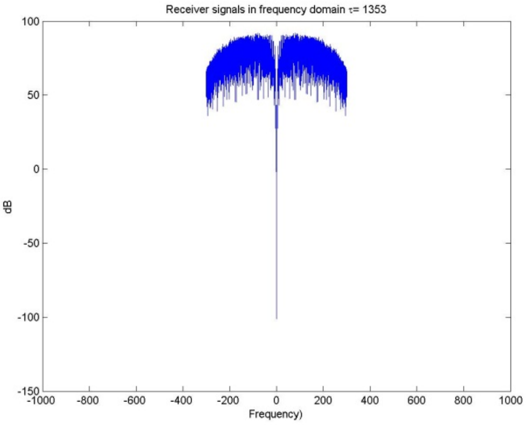
500 km





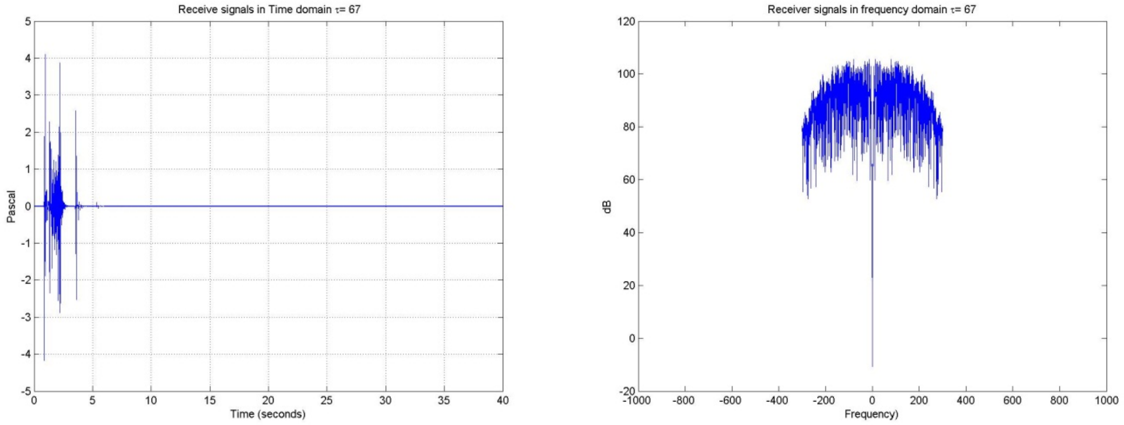
1000 km



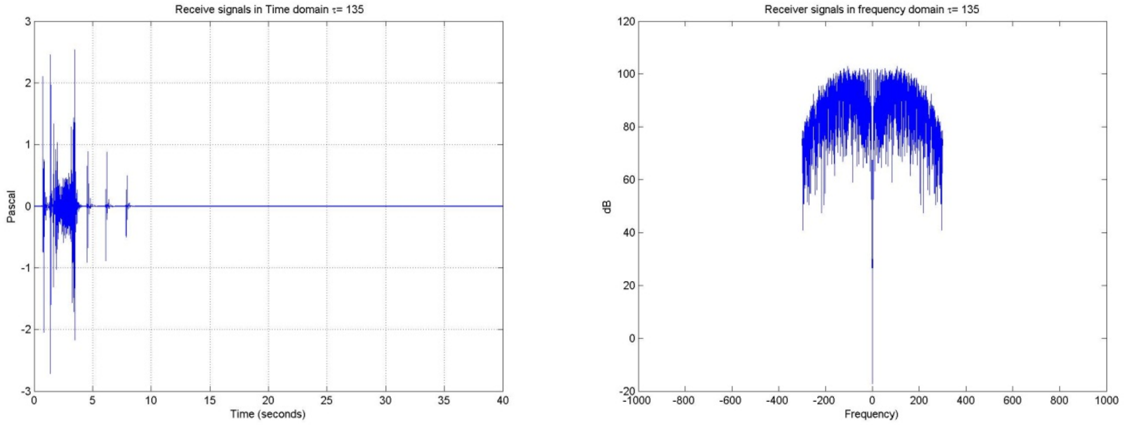


2000 km

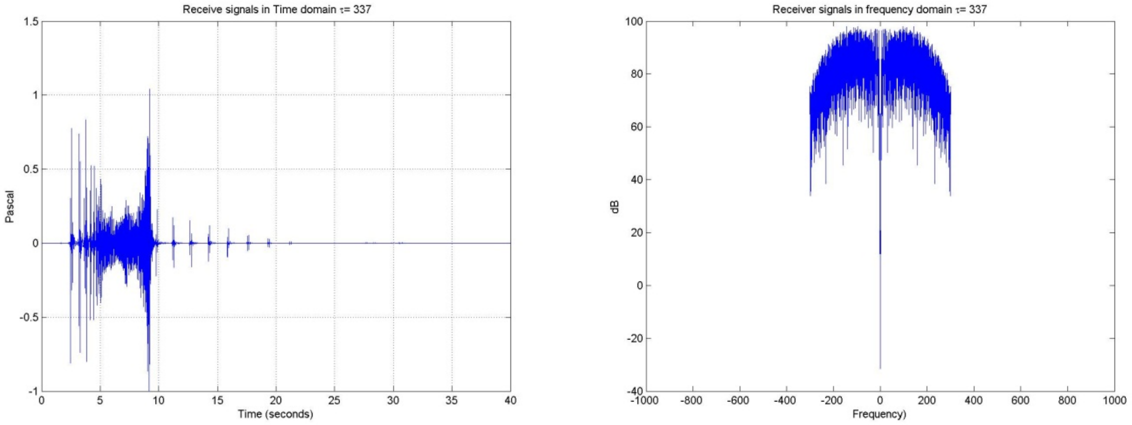
Receiver depth 200m



100 km



200 km



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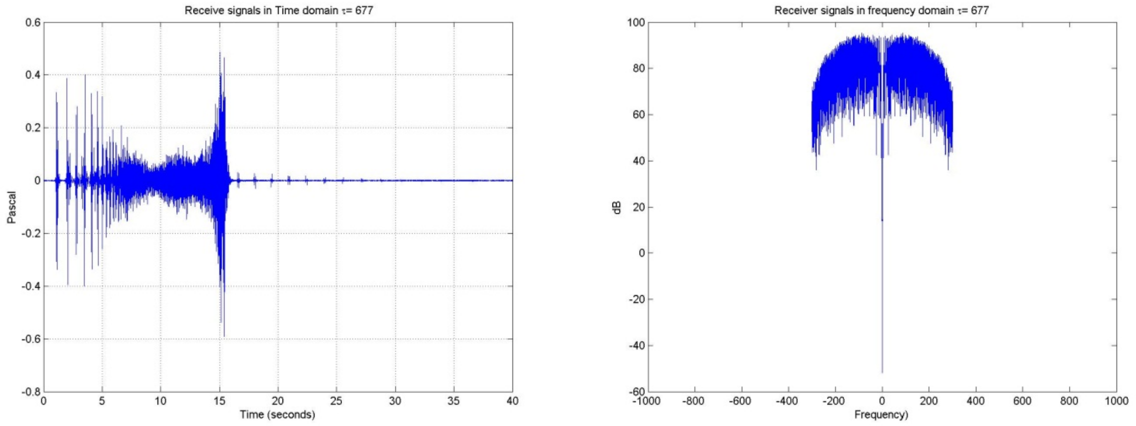
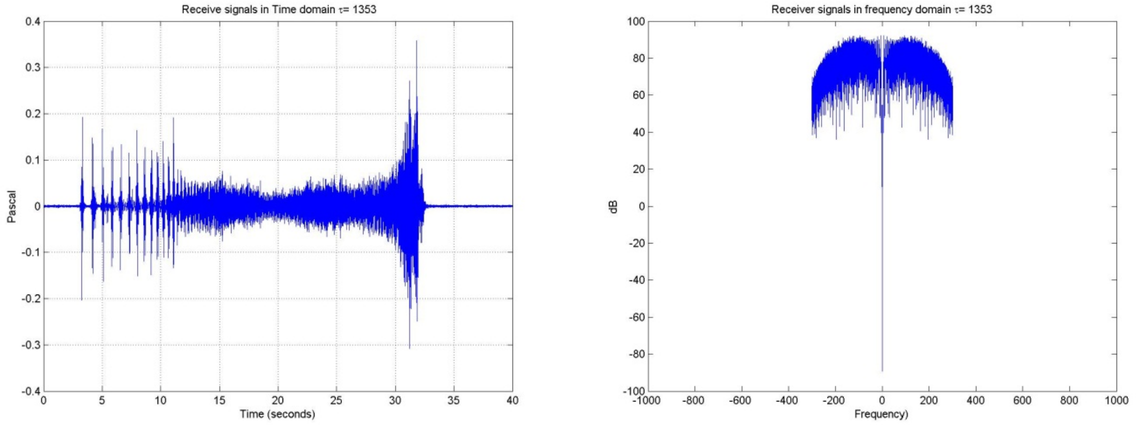


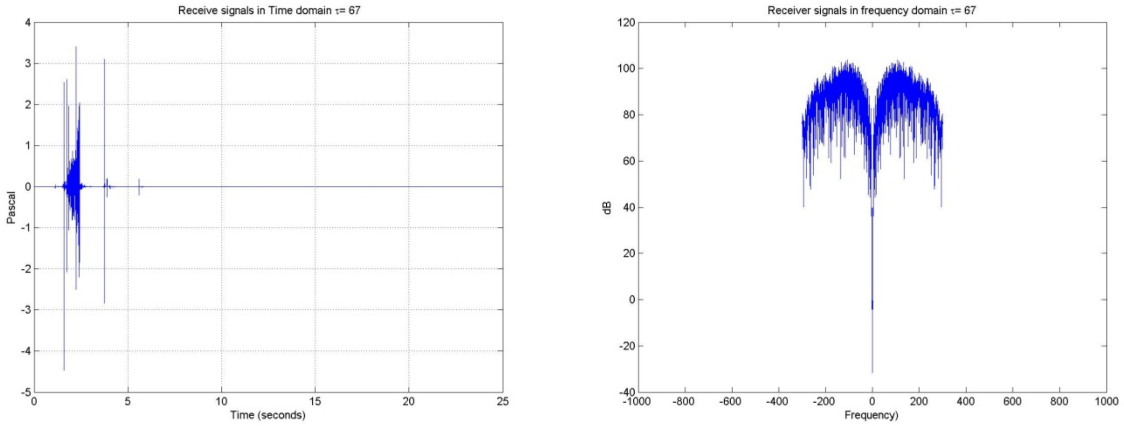
1000 km



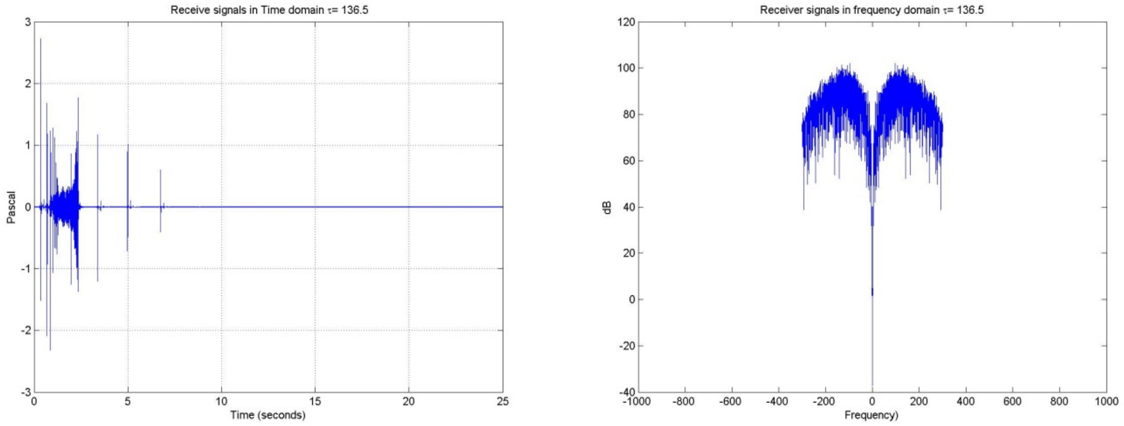
2000 km

11.3.1.2 Station 25

Receiver depth 10 m



100 km



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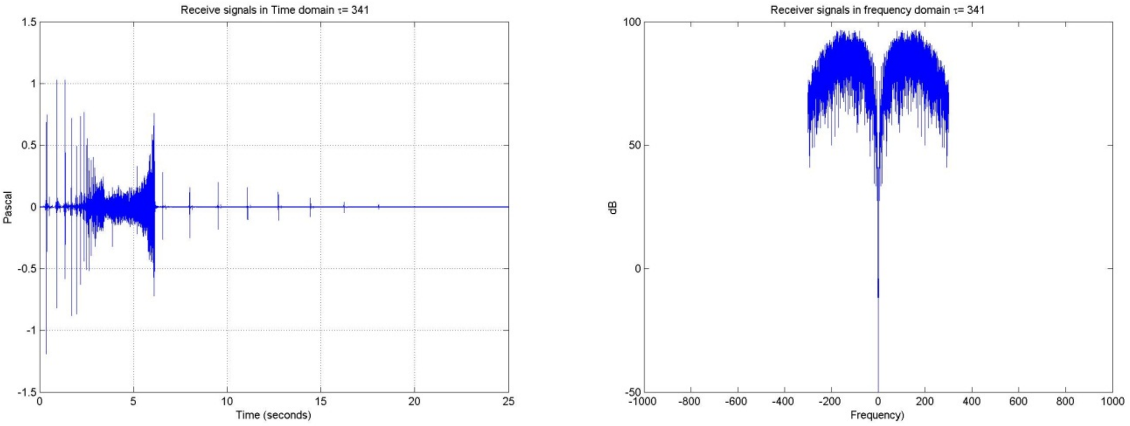

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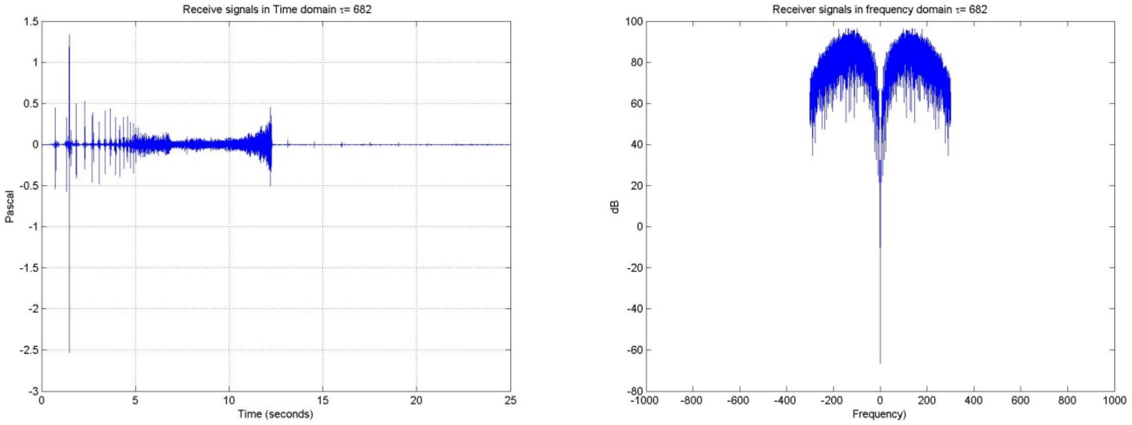

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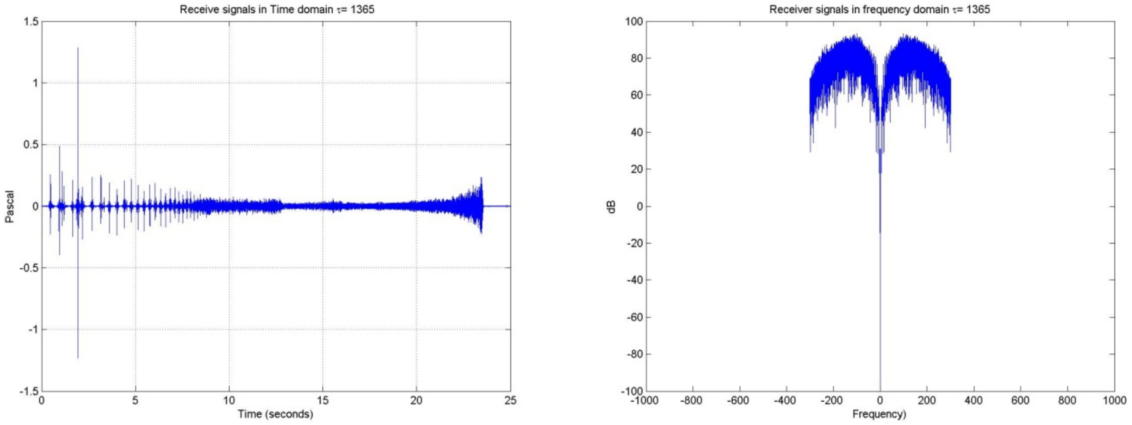
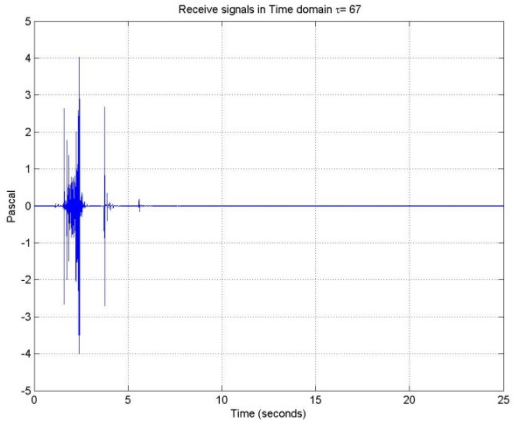
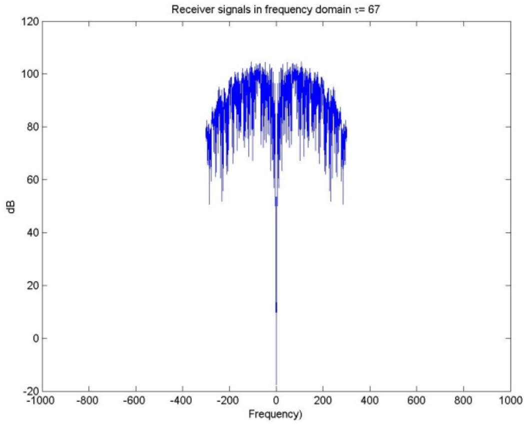


2000 km

Receiver depth 50 m





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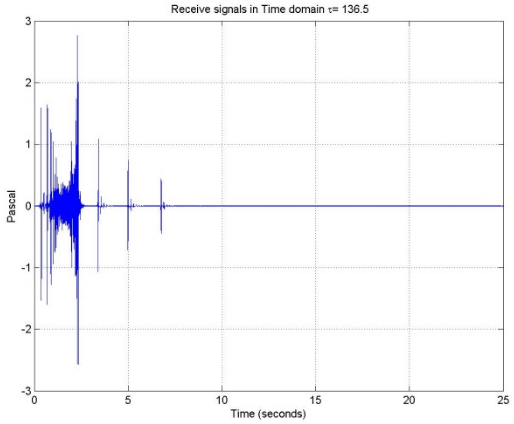

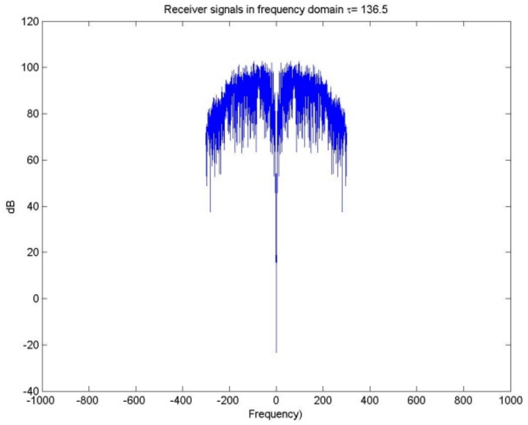

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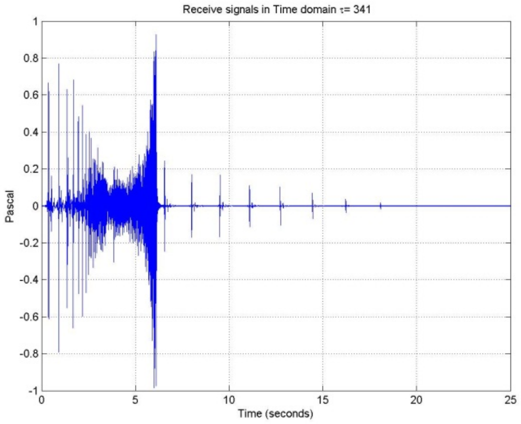

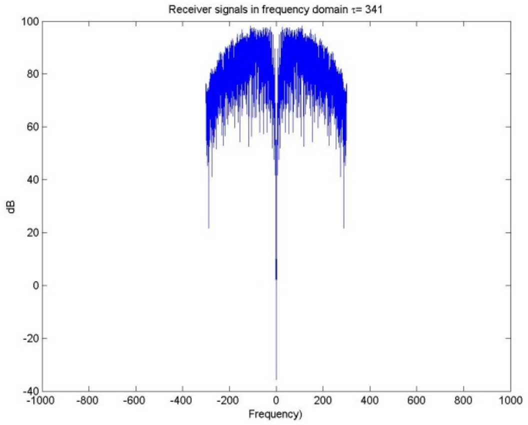

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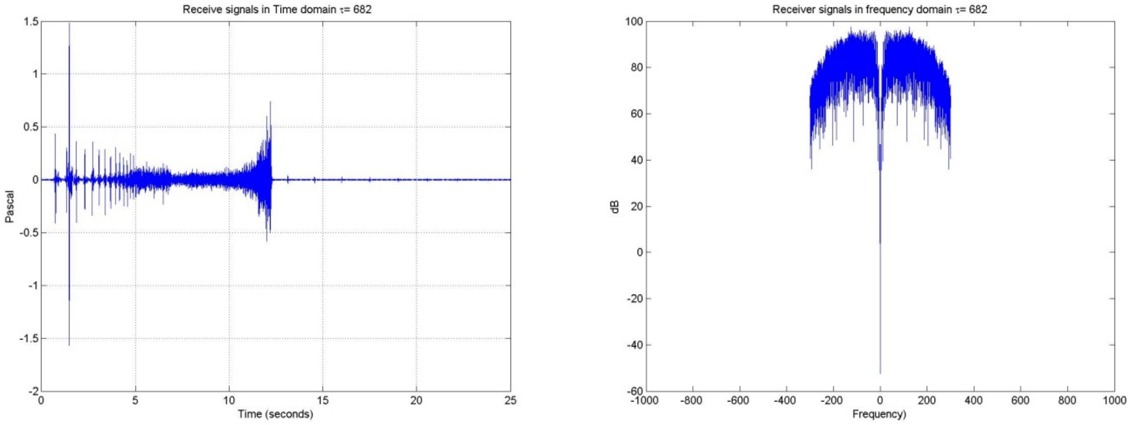

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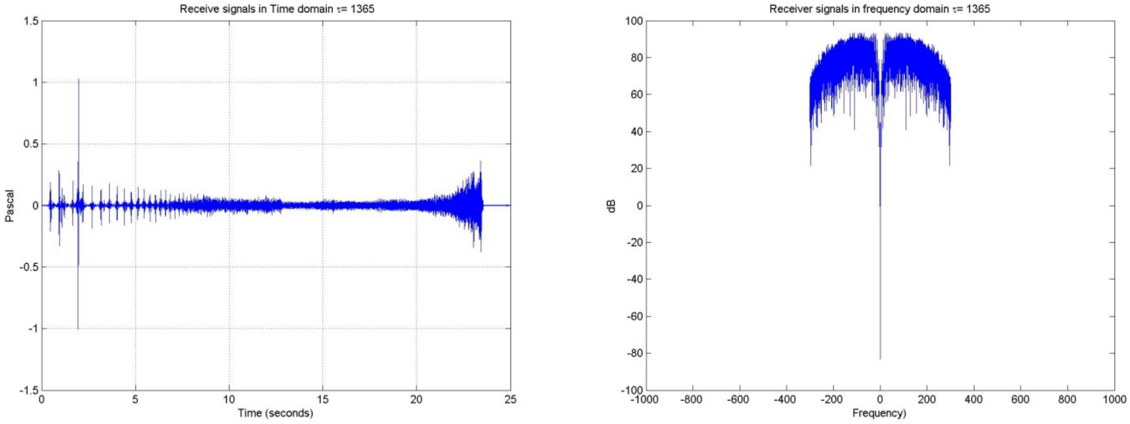
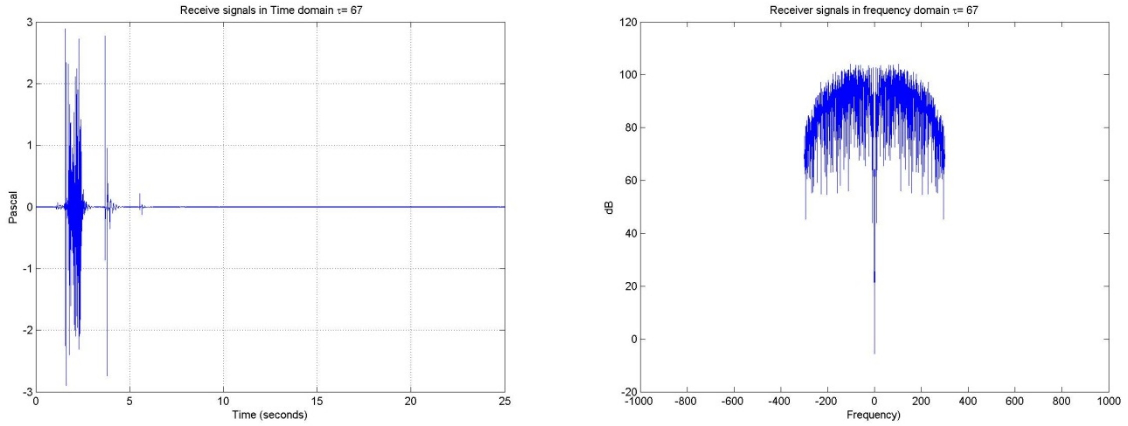


2000 km

Receiver depth 200 m



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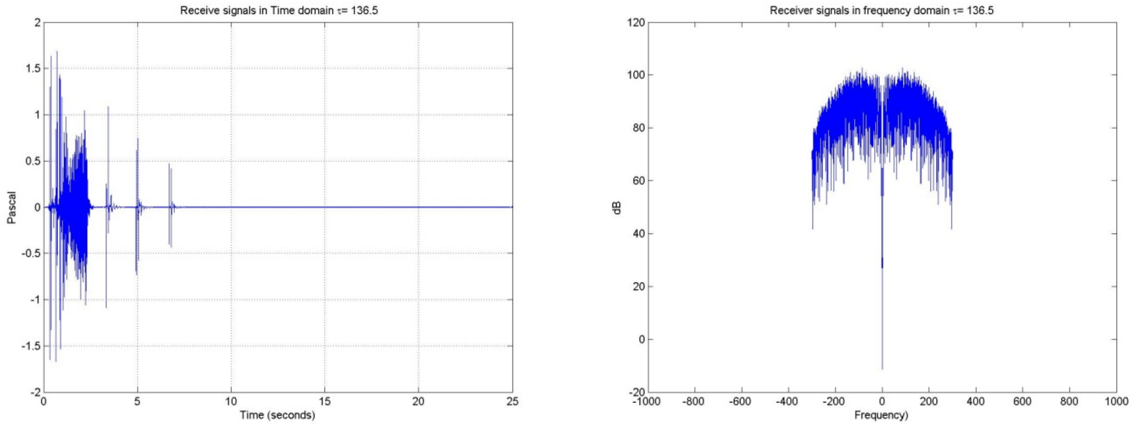

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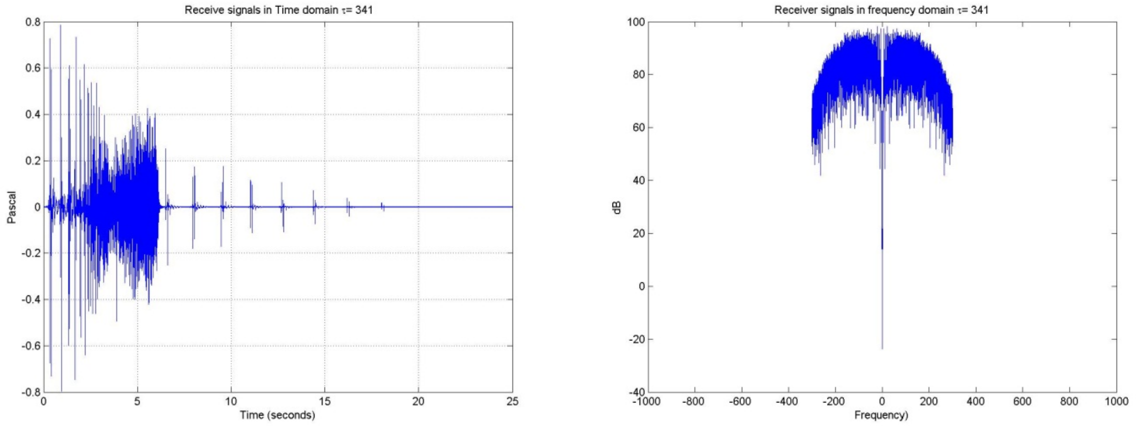

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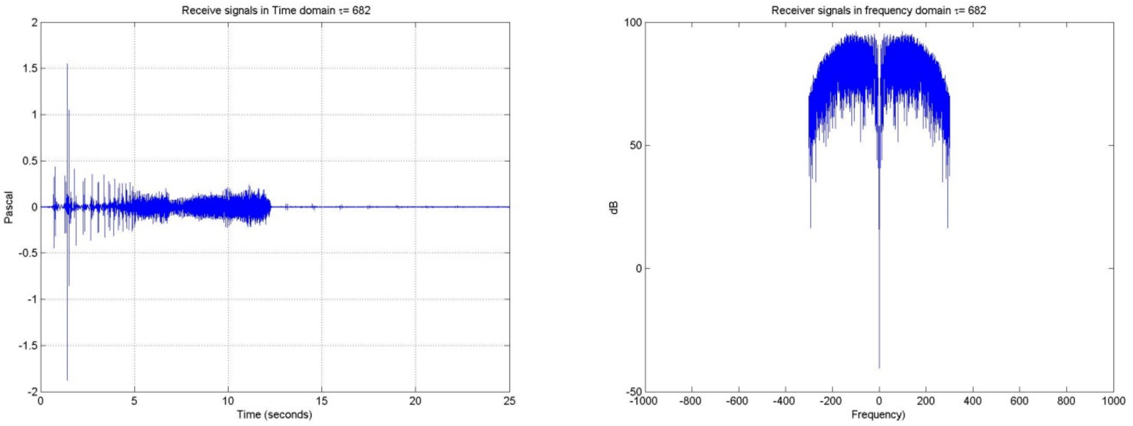

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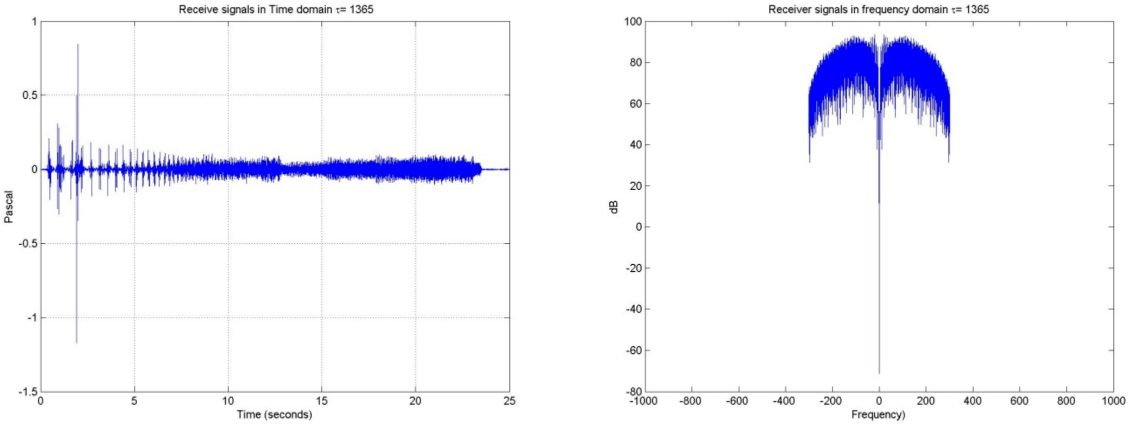
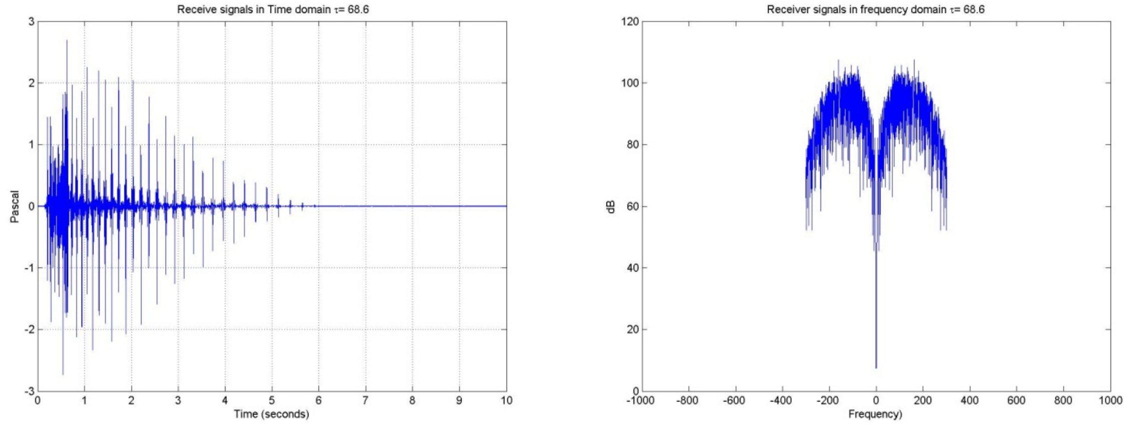


2000 km

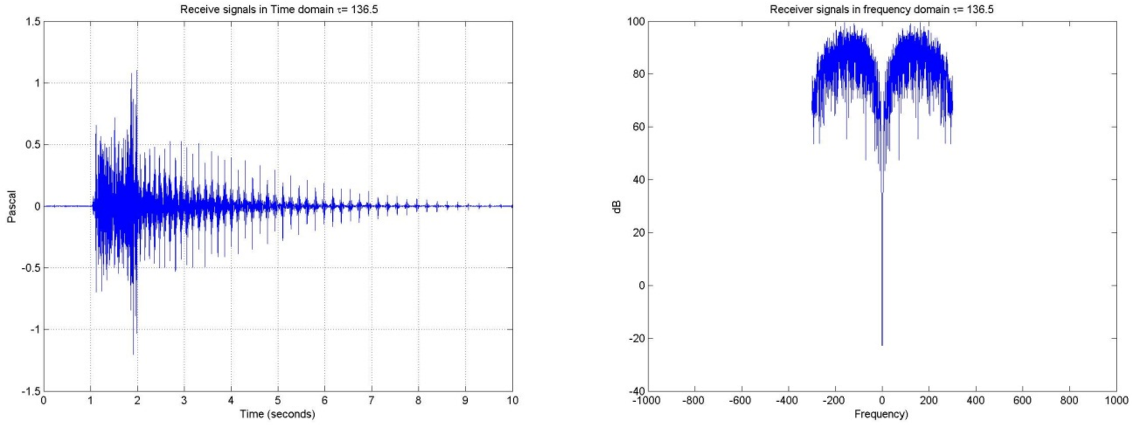
11.3.2 Depth 500 m

11.3.2.1 Station 715

Receiver depth 10 m



100 km



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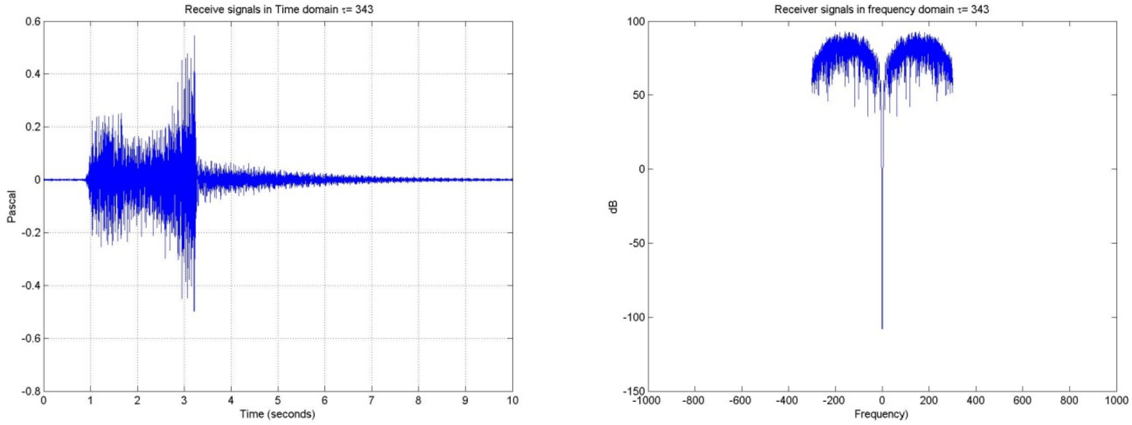
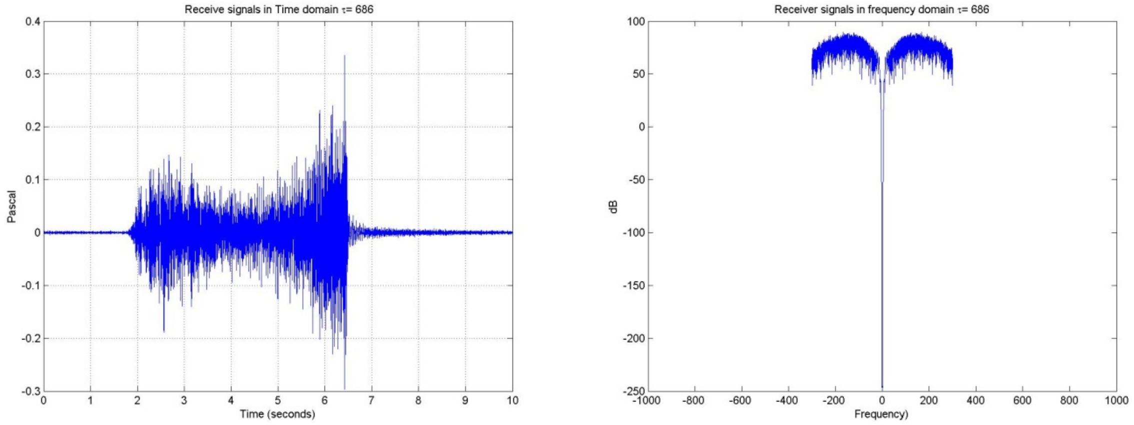
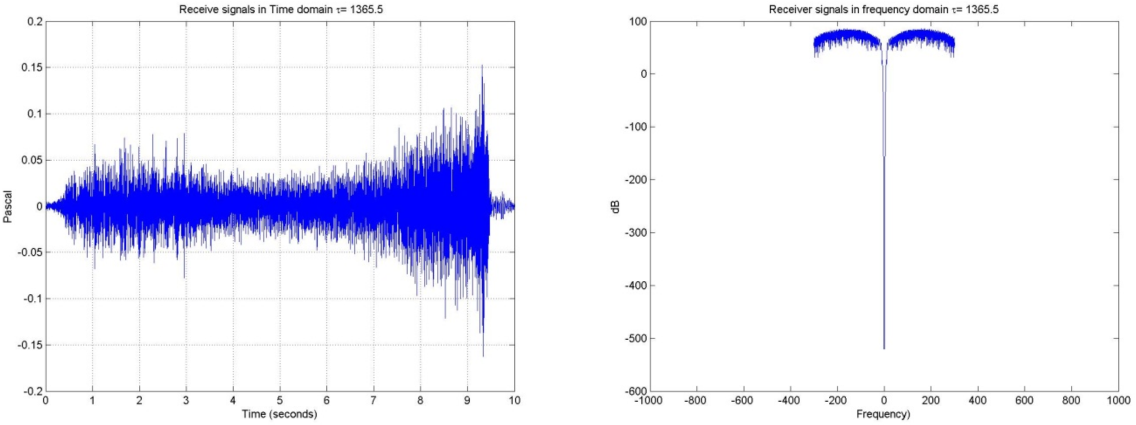


500 km

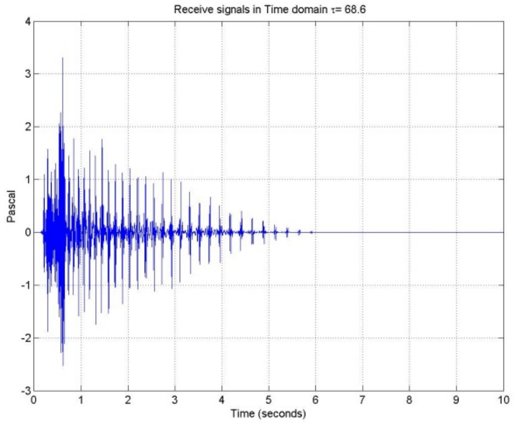


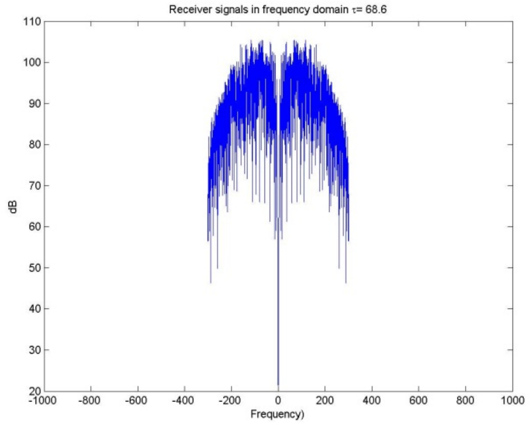
1000 km



2000 km

Receiver depth 50 m





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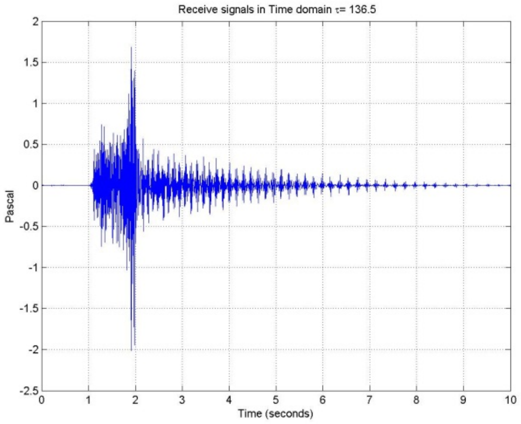
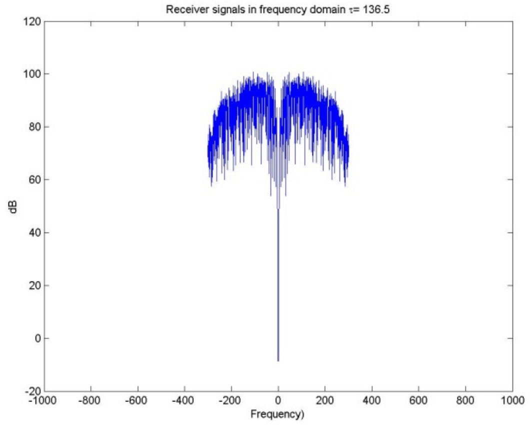
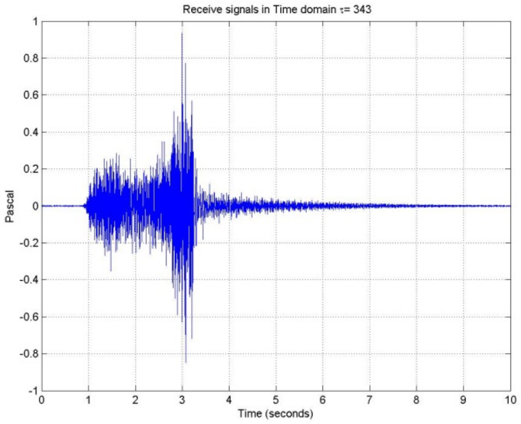
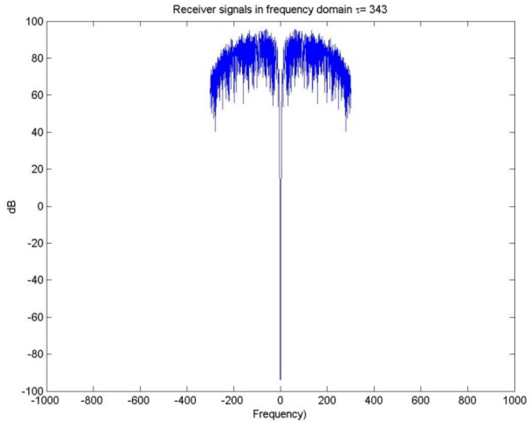


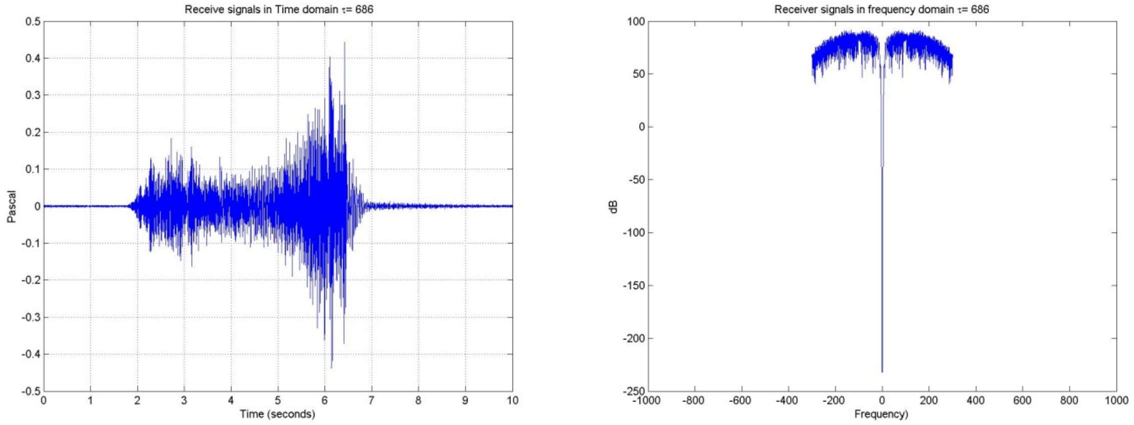


200 km





500 km



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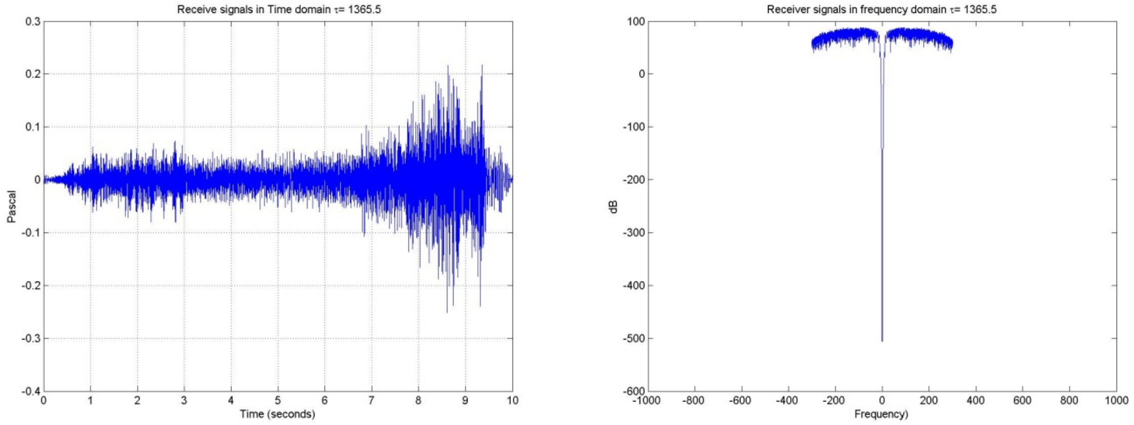
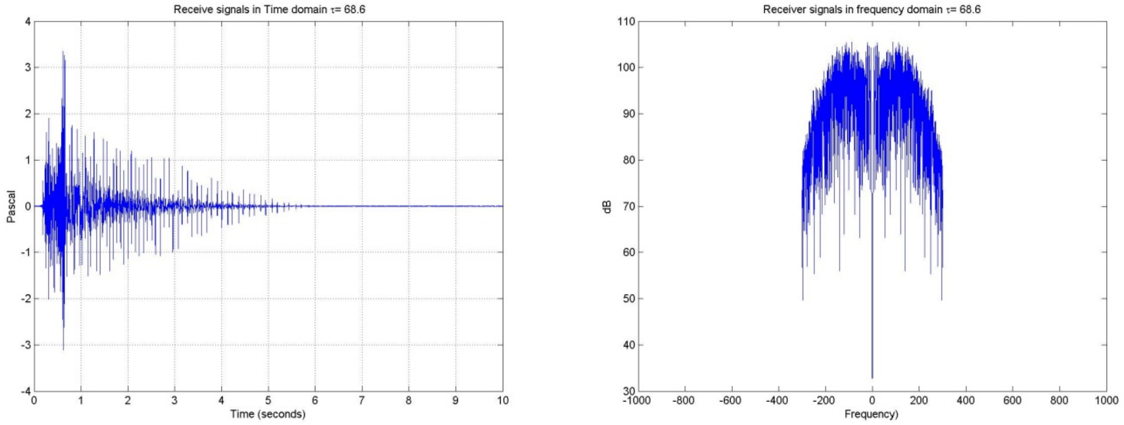
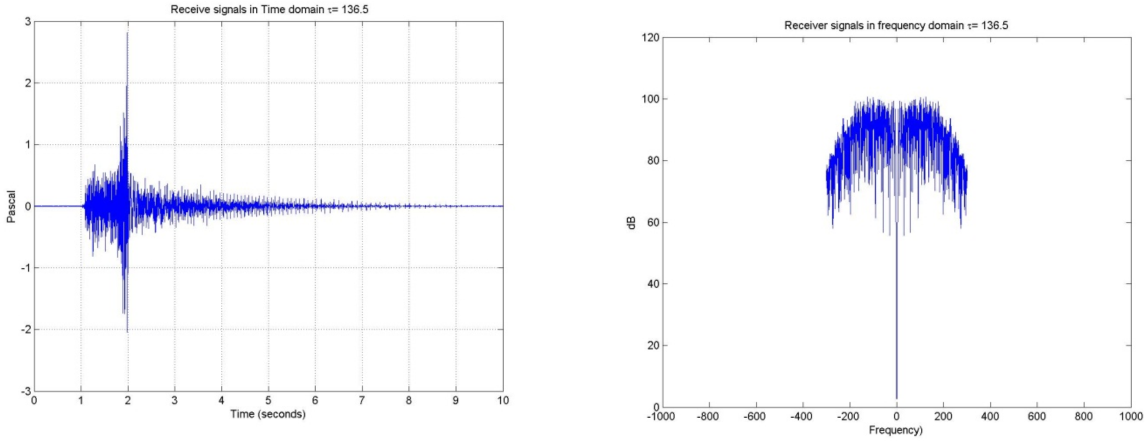


2000 km

Receiver depth 200 m



100 km



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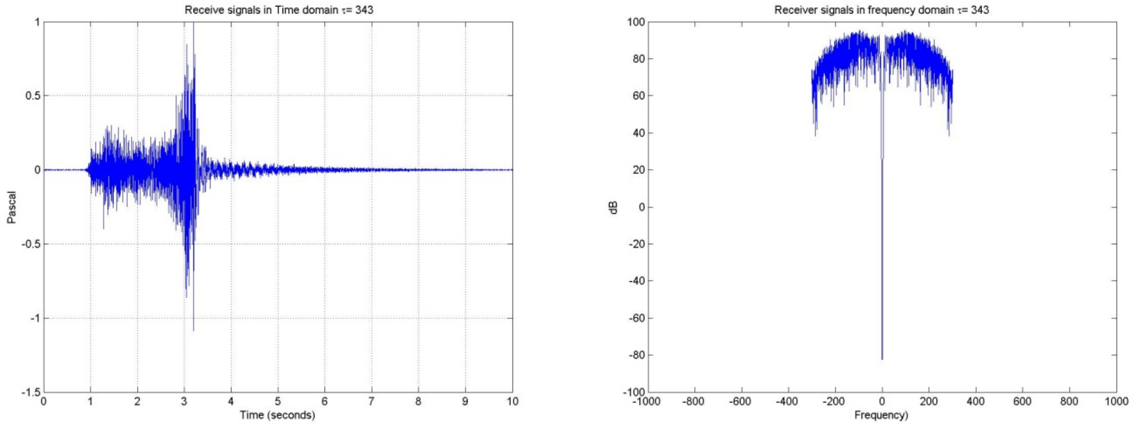
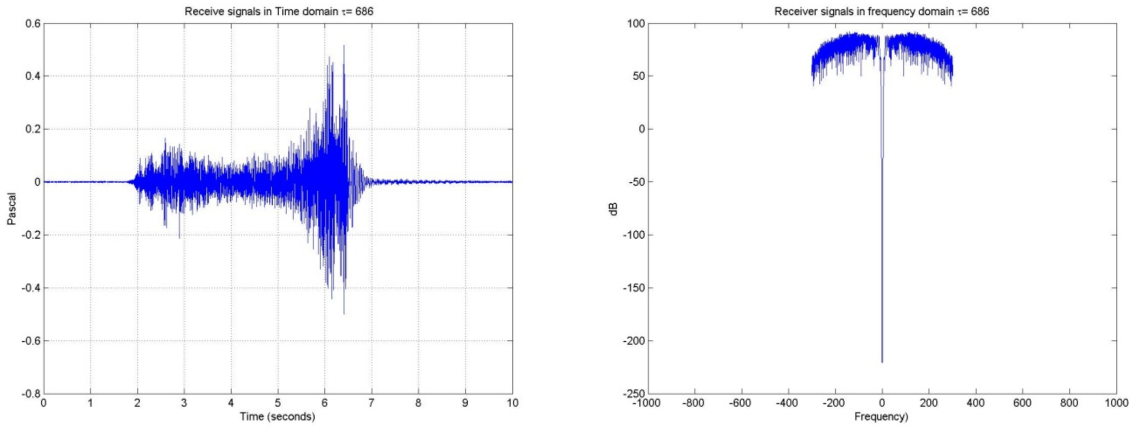
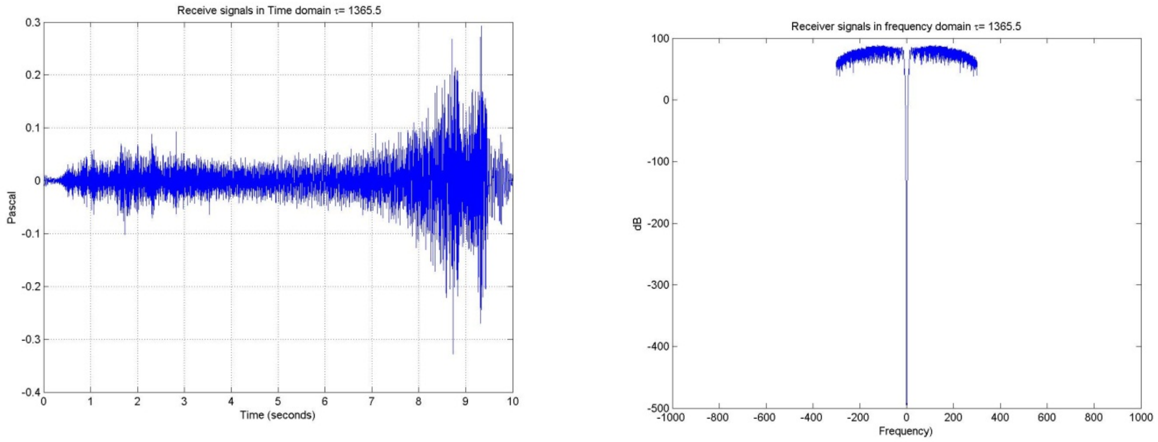


500 km


Receive signals in Time domain τ= 686

Receiver signals in frequency domain τ= 686

1000 km

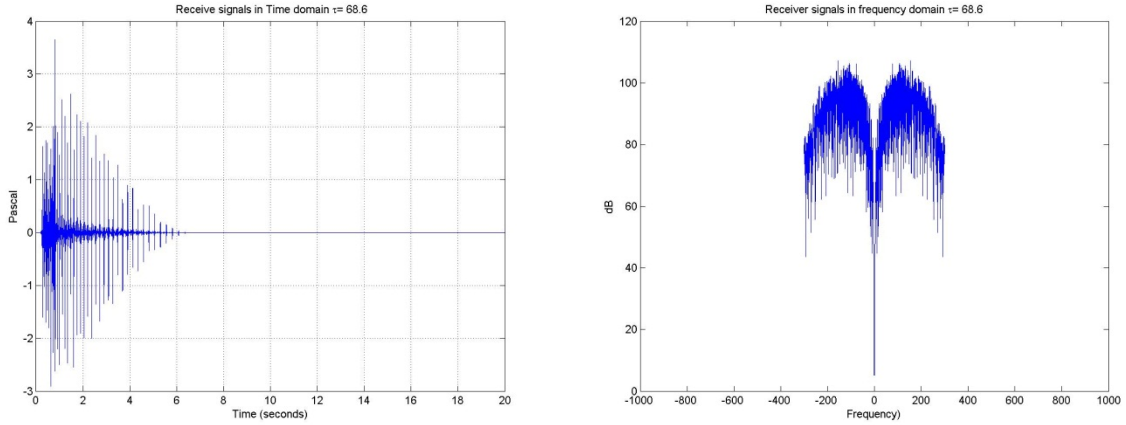

Receive signals in Time domain τ= 1365.5

Receiver signals in frequency domain τ= 1365.5

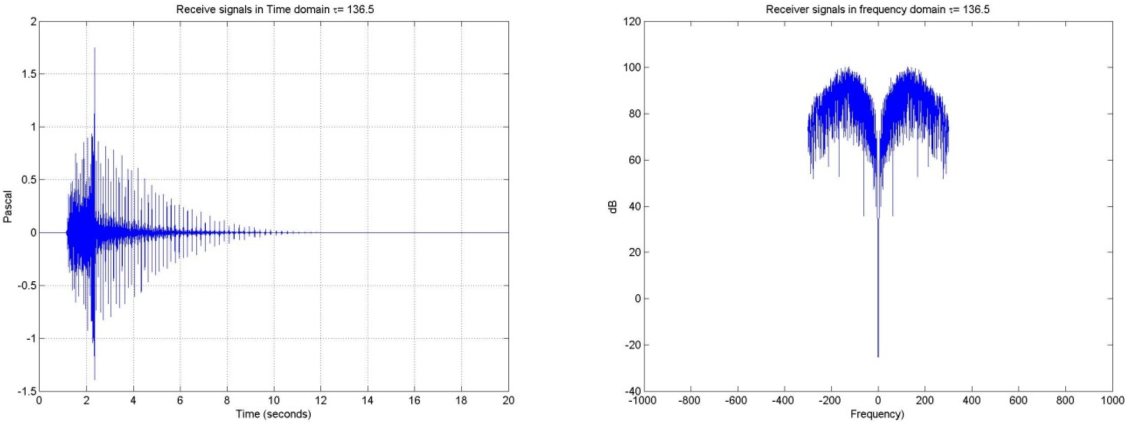
2000 km

11.3.2.2 Station 25

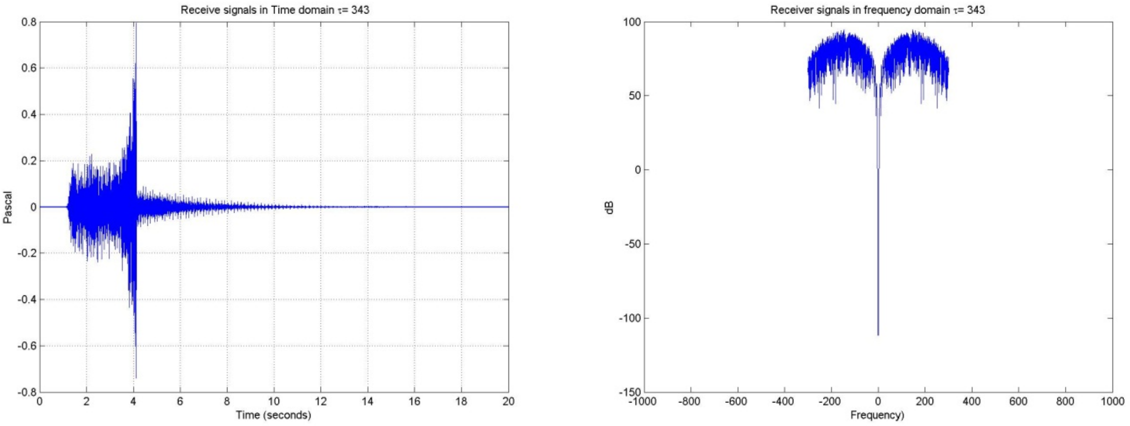
Receiver depth 10 m



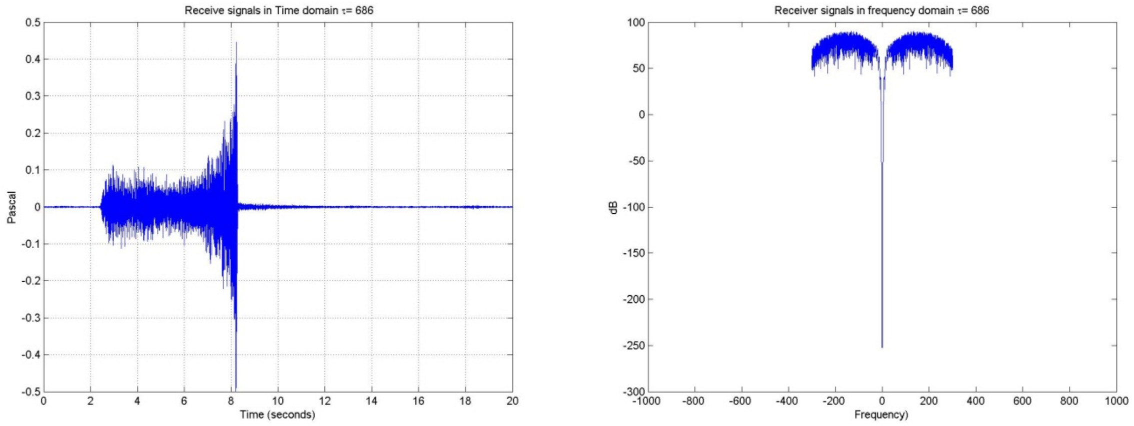
100 km



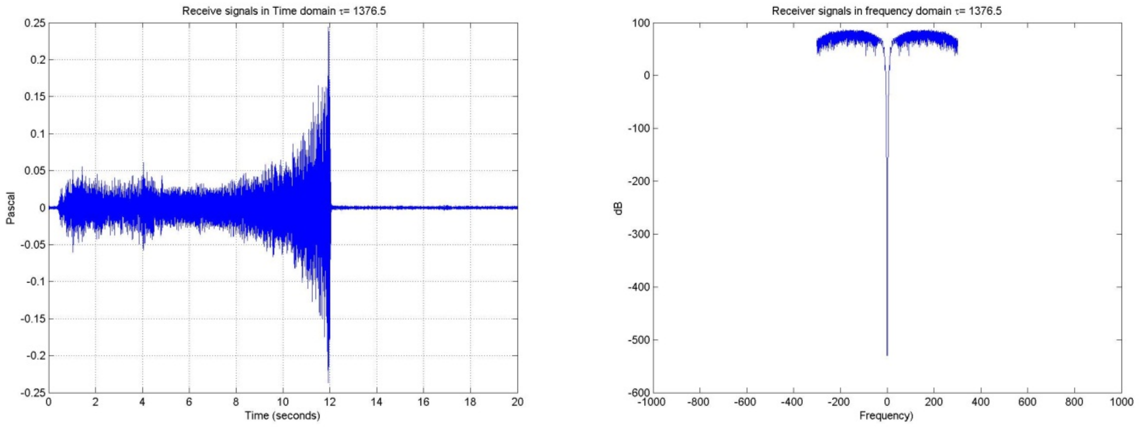
200 km



500 km

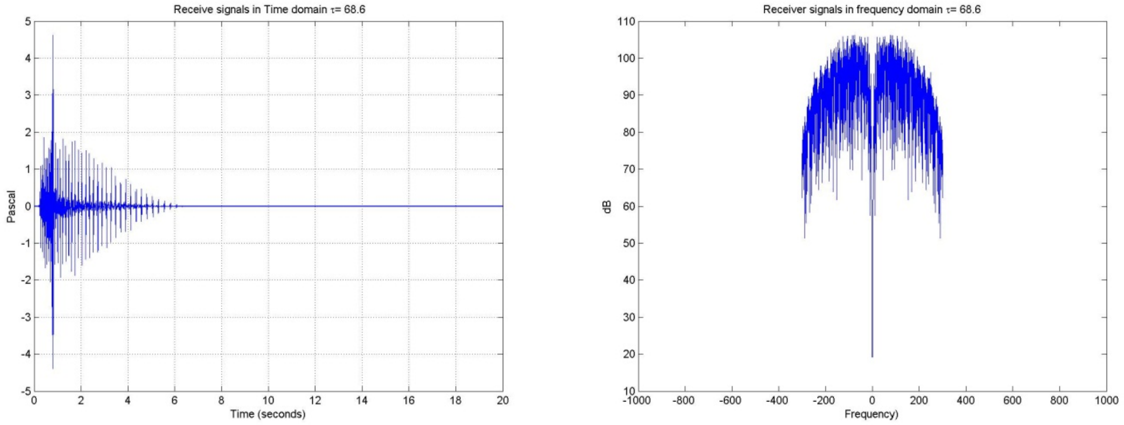


1000 km

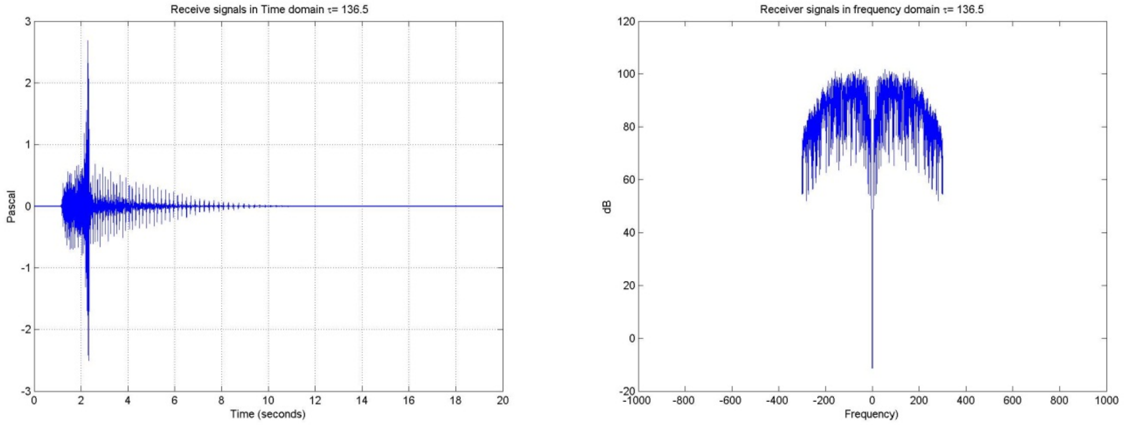


2000 km

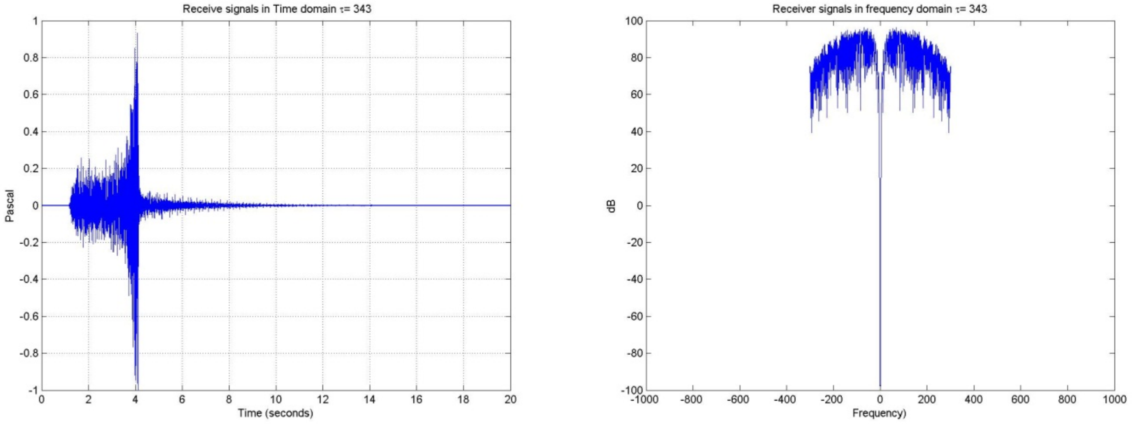
Receiver depth 50 m



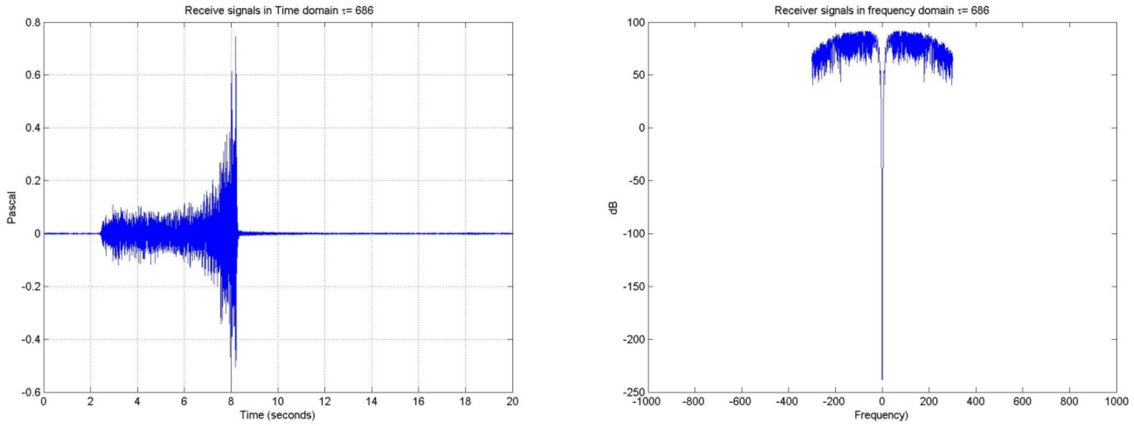
100 km



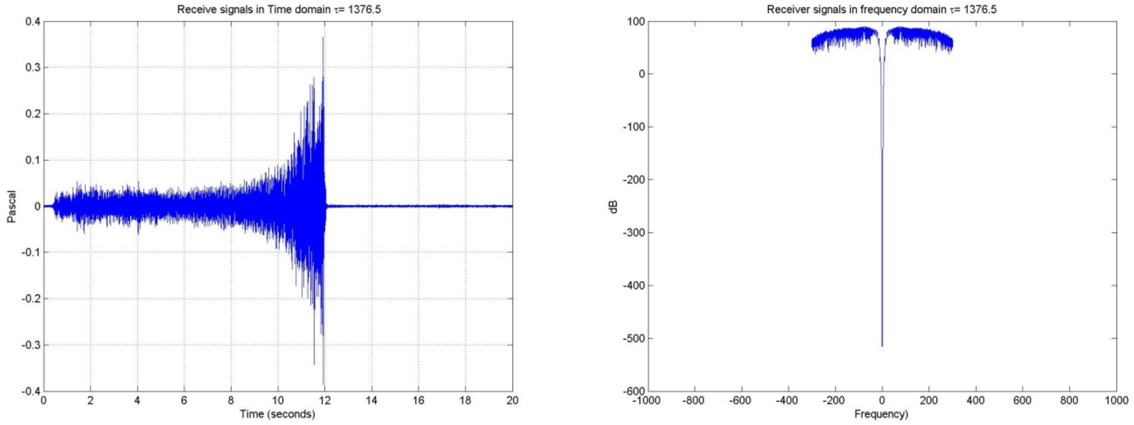
200 km



500 km

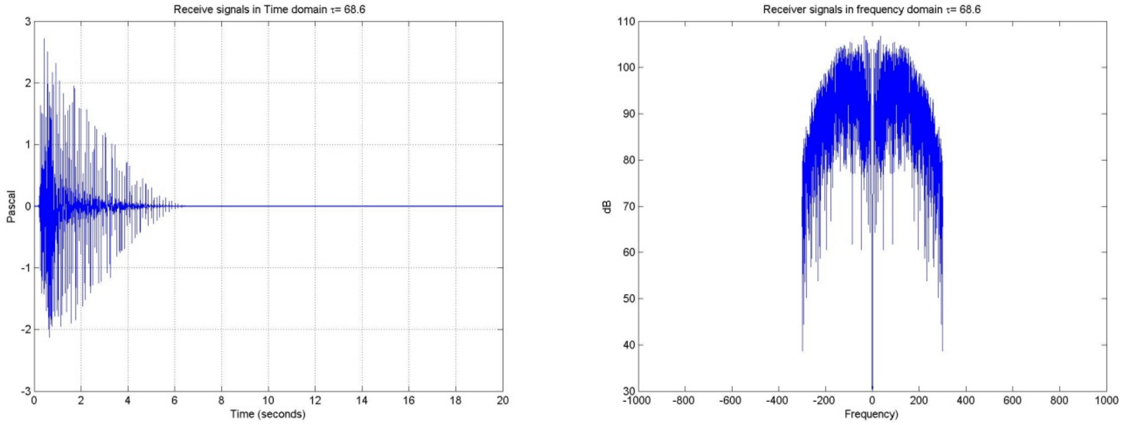


1000 km

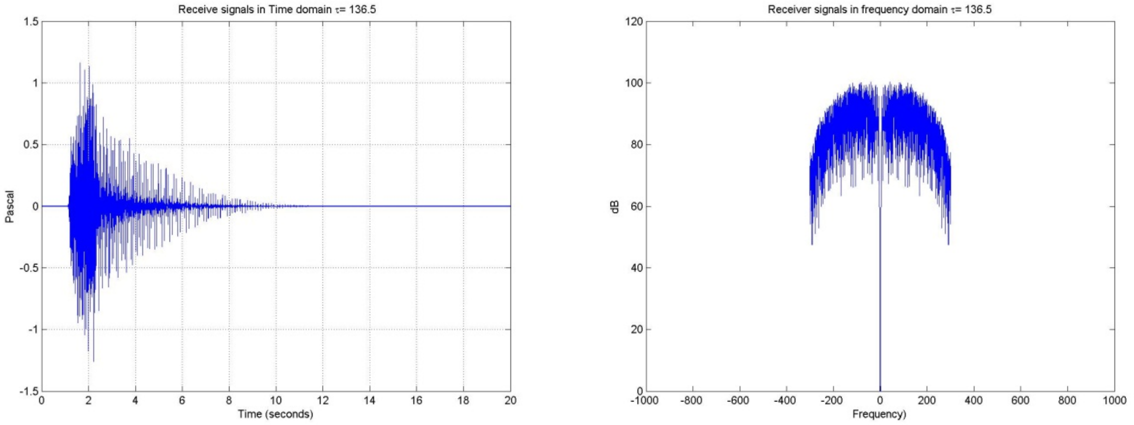


2000 km

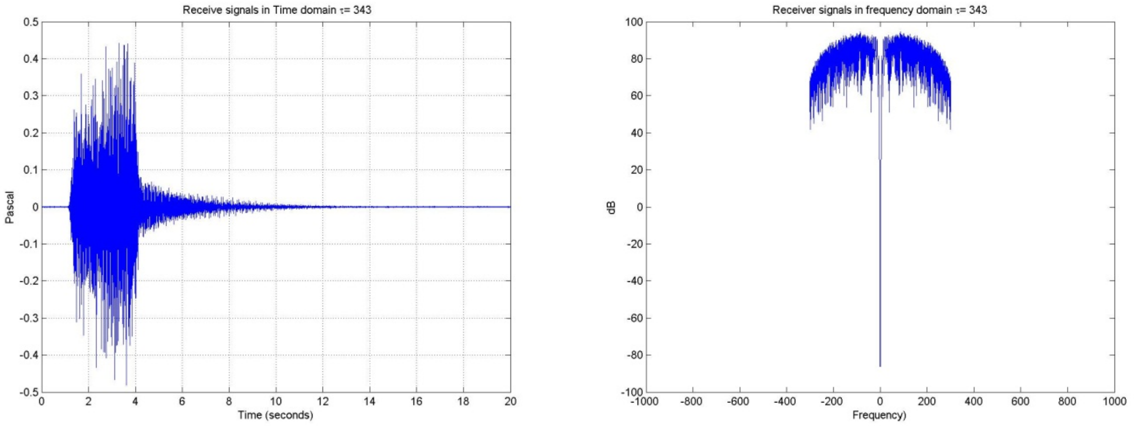
Receiver depth 200 m



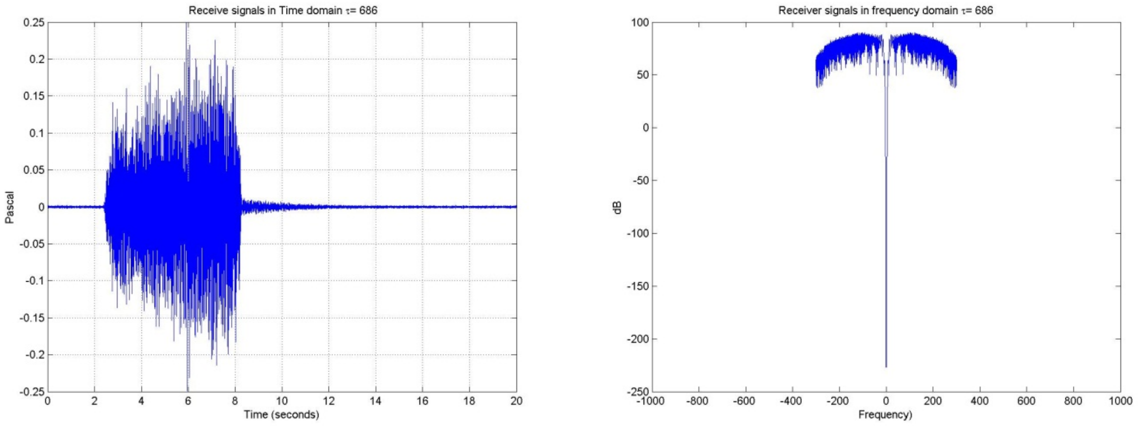
100 km



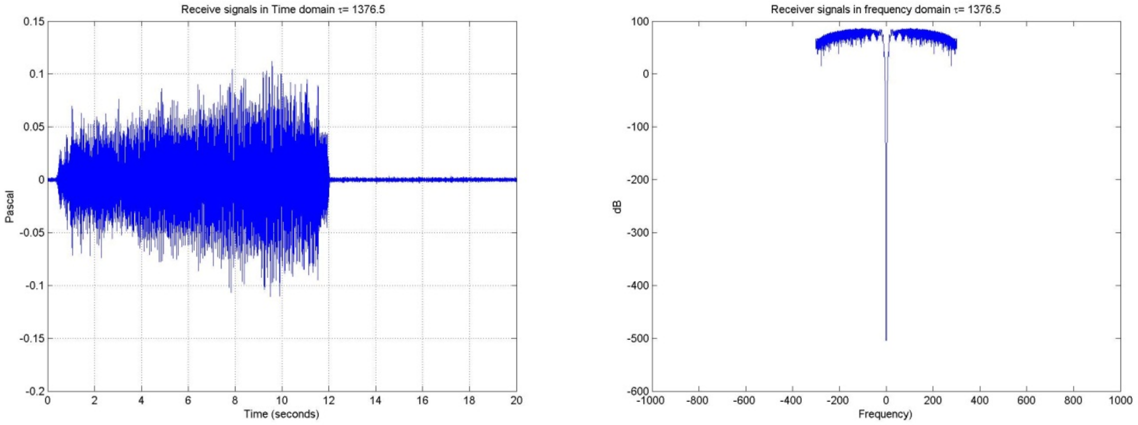
200 km



500 km



1000 km



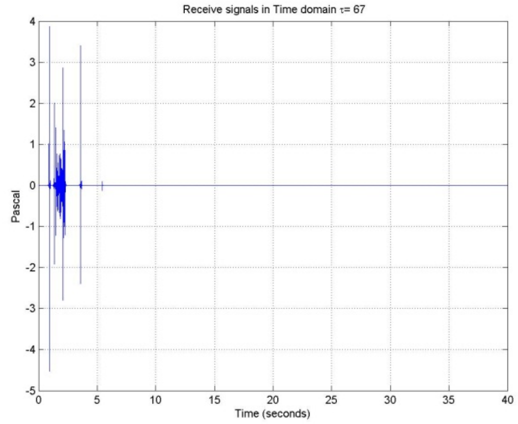
2000 km

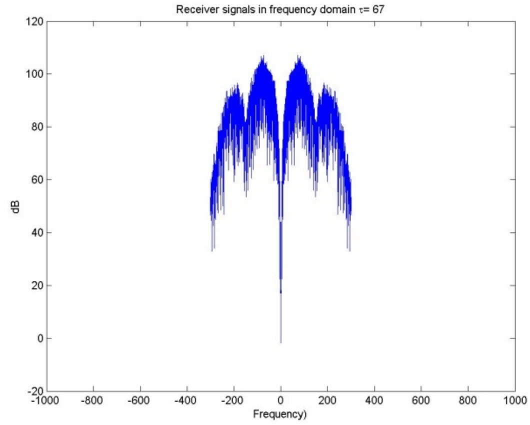
11.4 3 GI-gun Array, source depth 5 m

11.4.1 Depth 4000 m

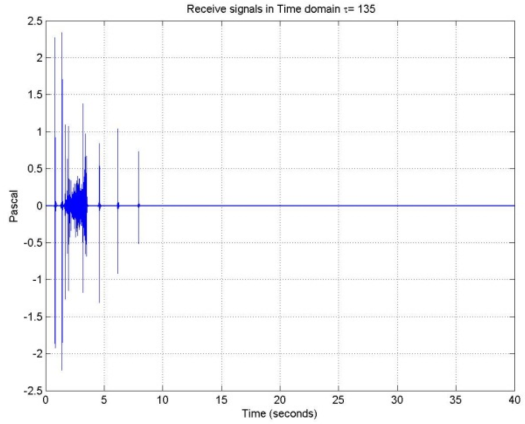
11.4.1.1 Station 715

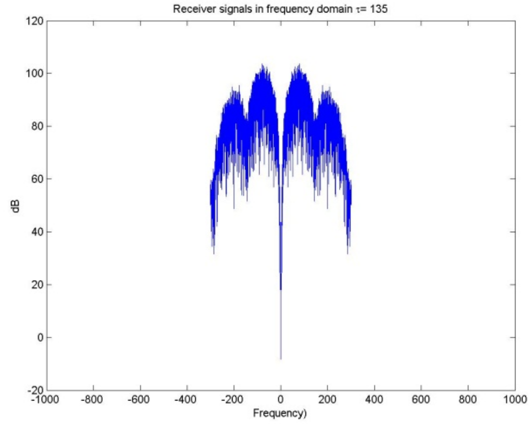
Receiver depth 10m



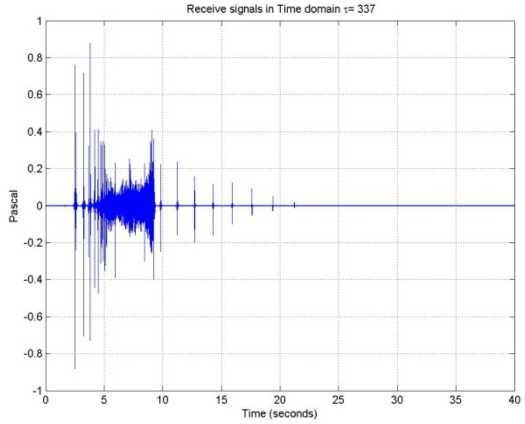


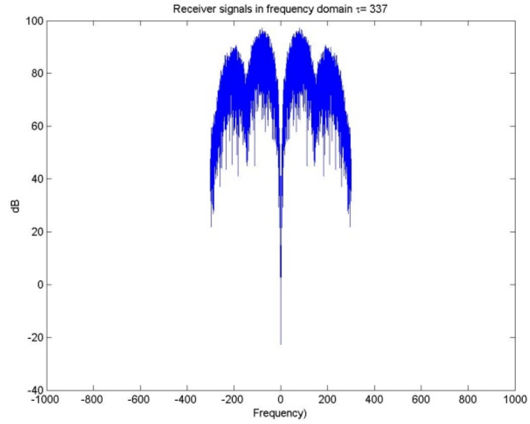
100 km



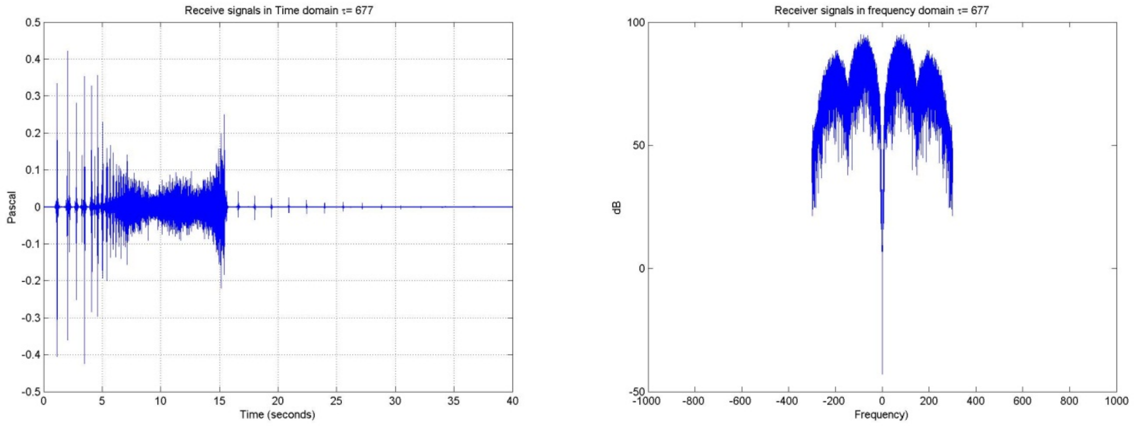


200 km

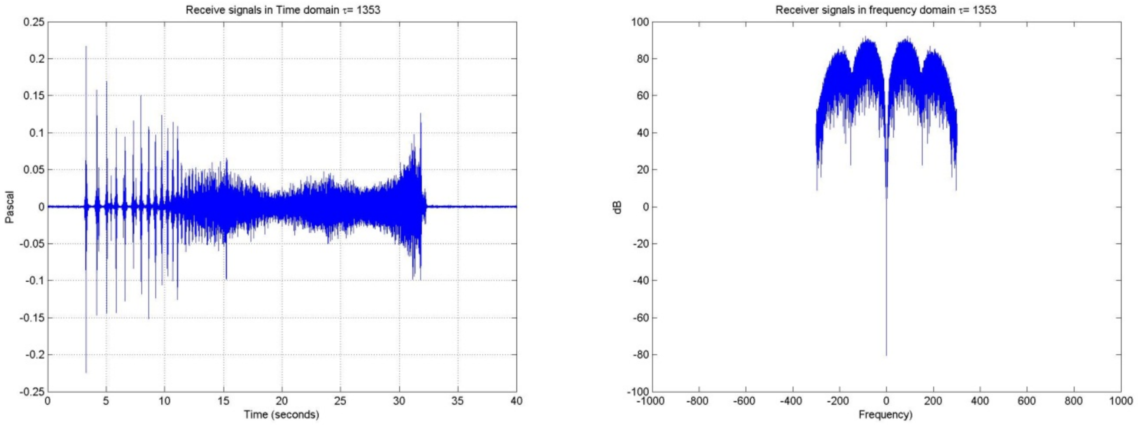




500 km

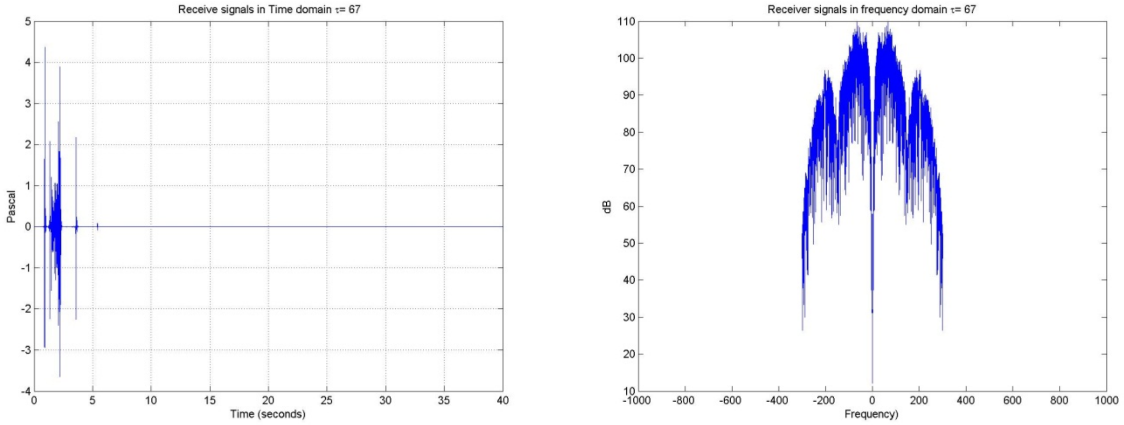


1000 km

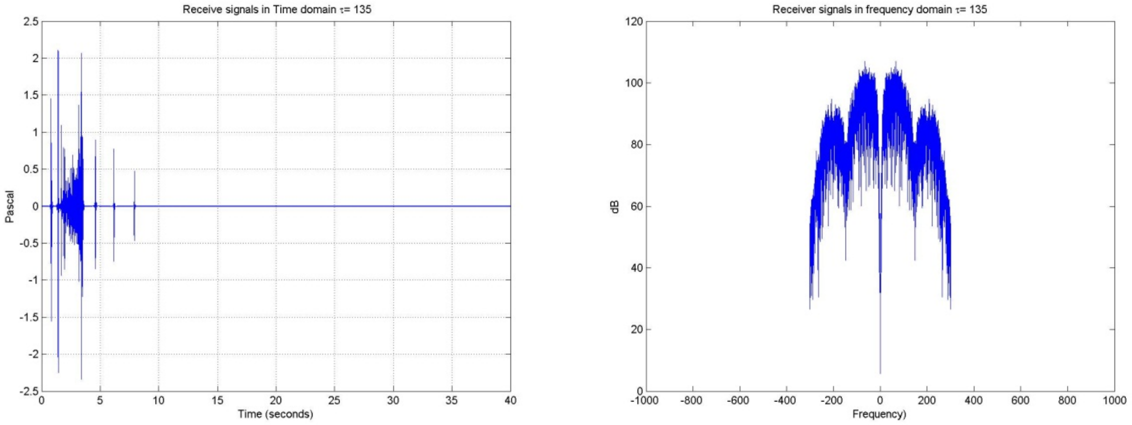


2000 km

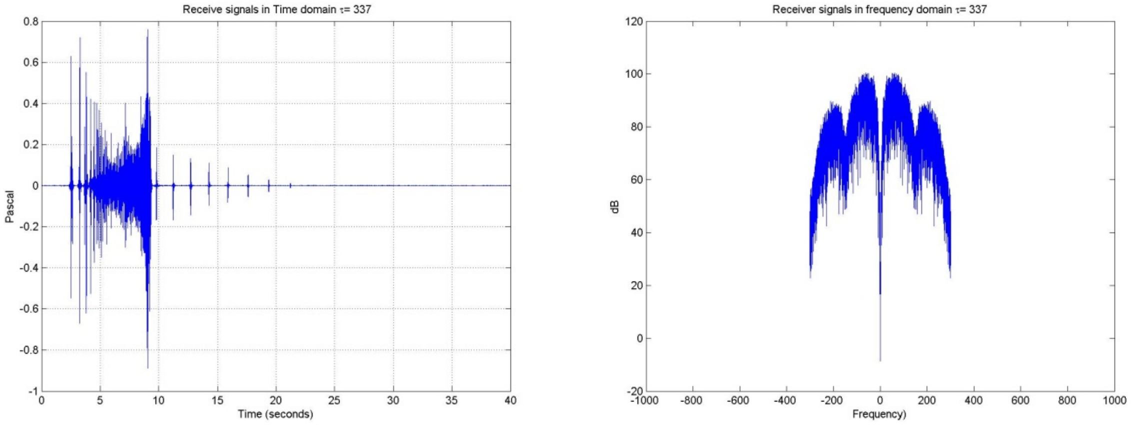
Receiver depth 50m



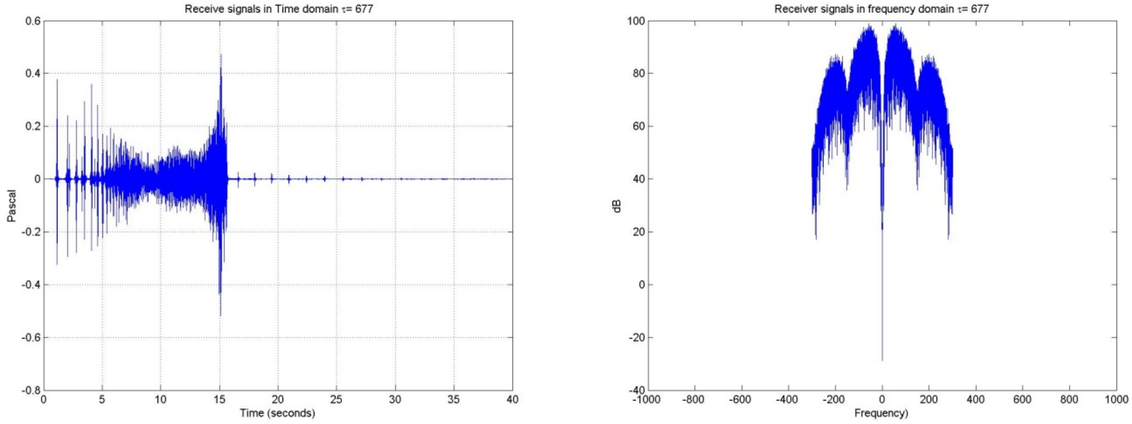
100 km



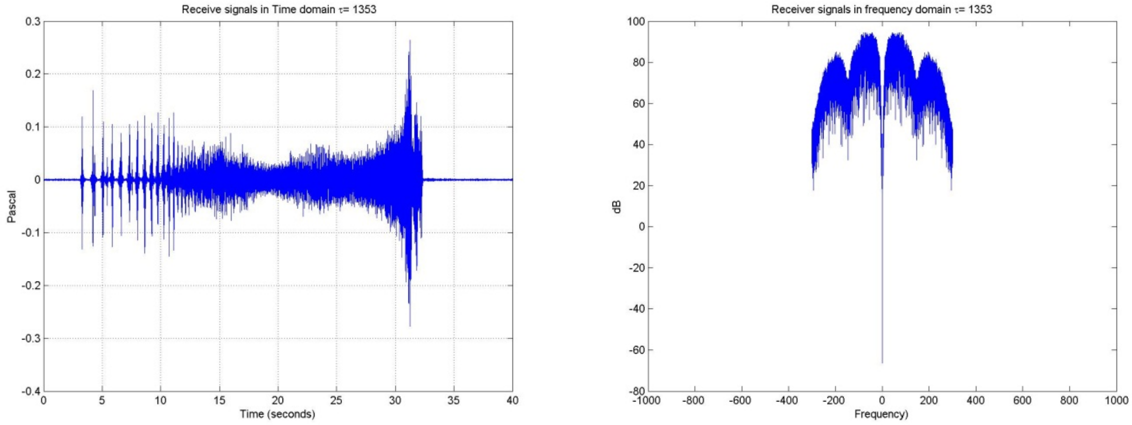
200 km



500 km

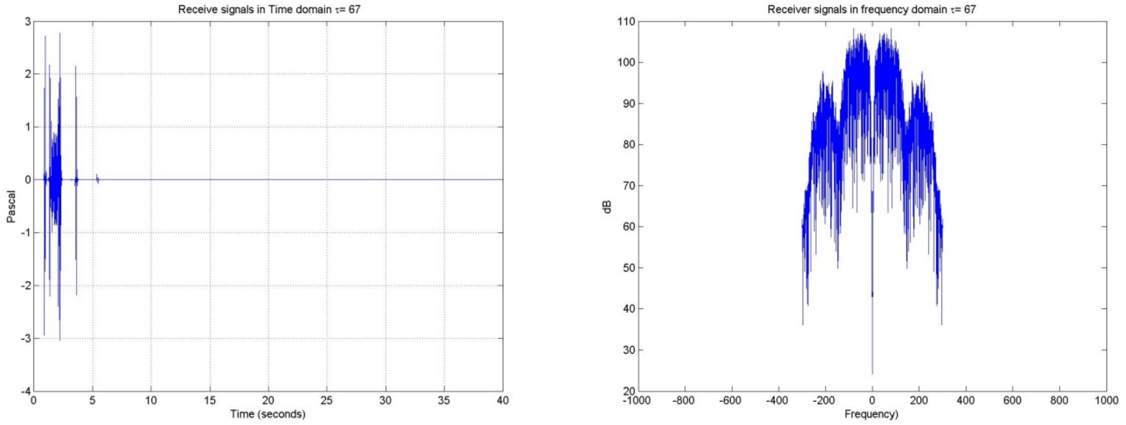


1000 km

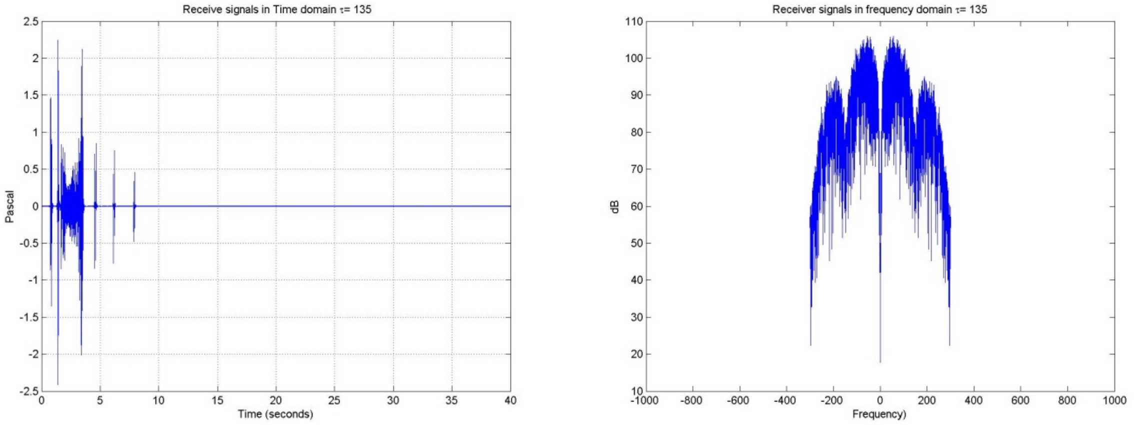


2000 km

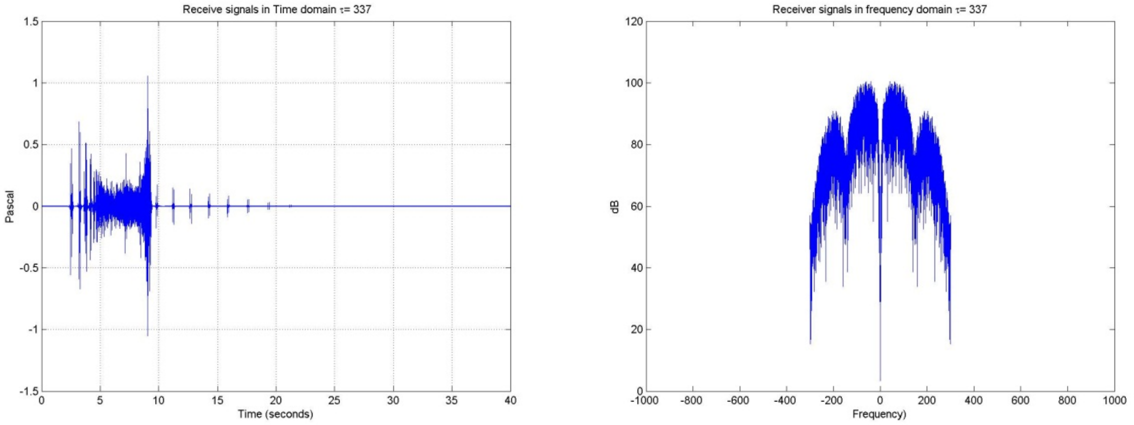
Receiver depth 200m



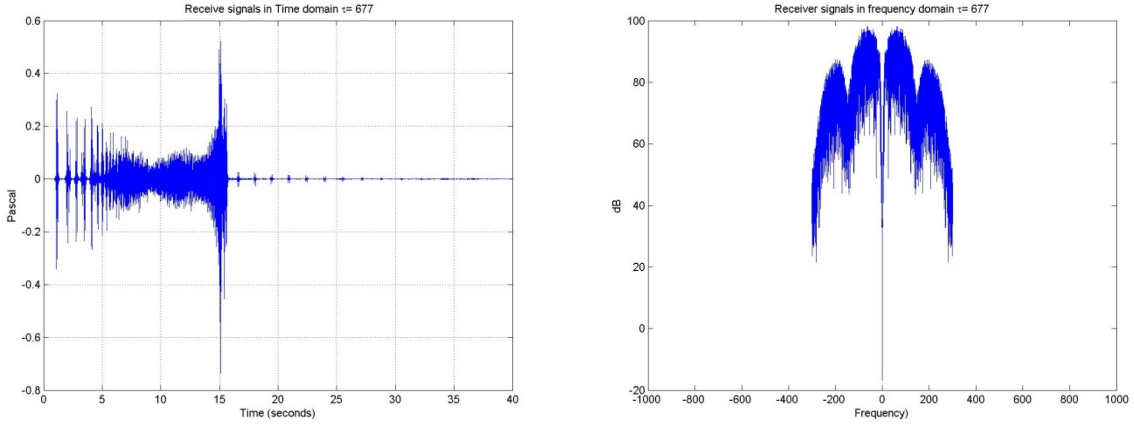
100 km



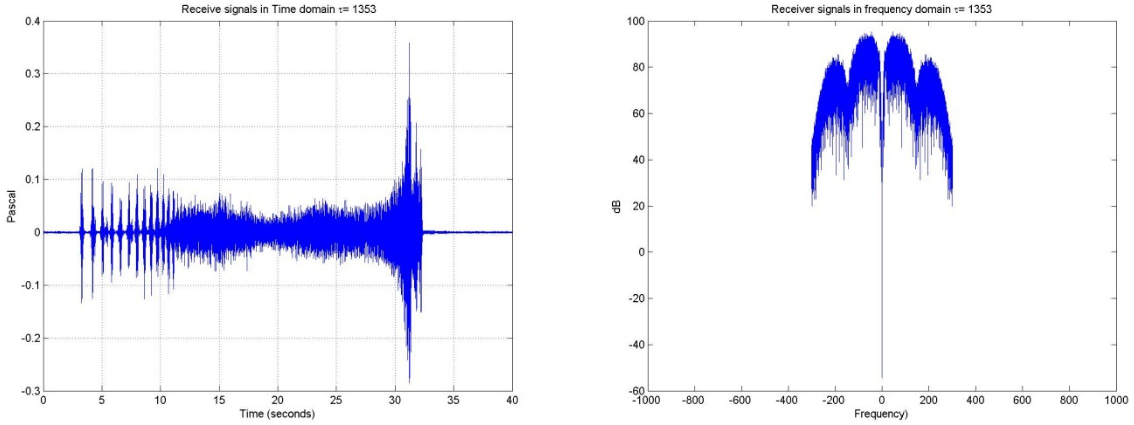
200 km



500 km



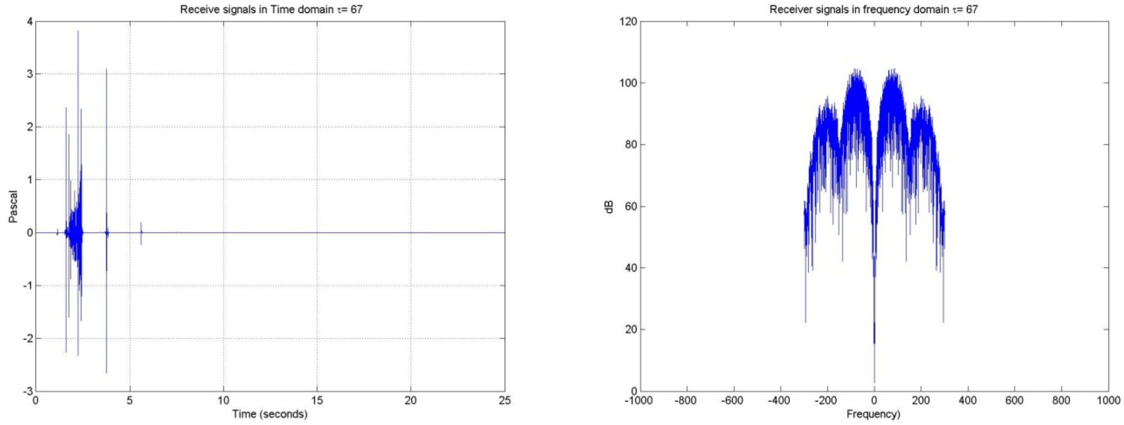
1000 km



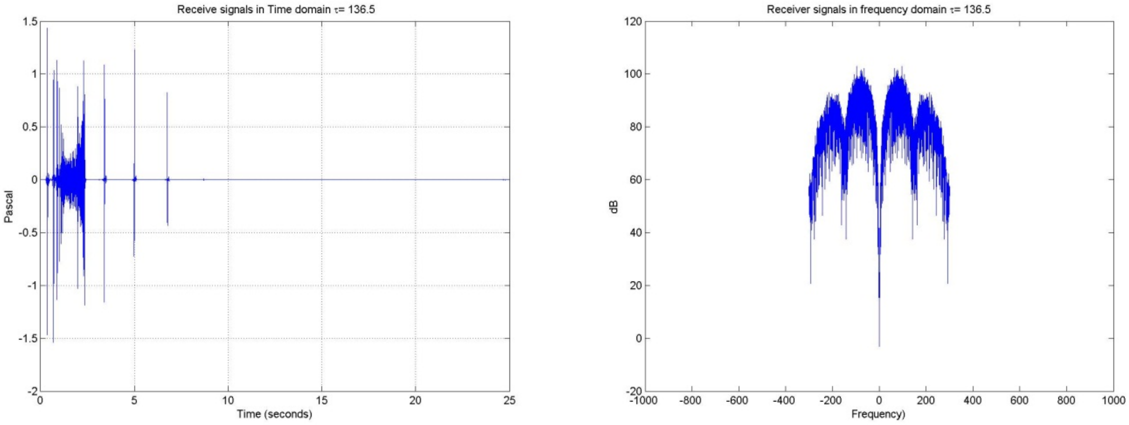
2000 km

11.4.1.2 Station 25

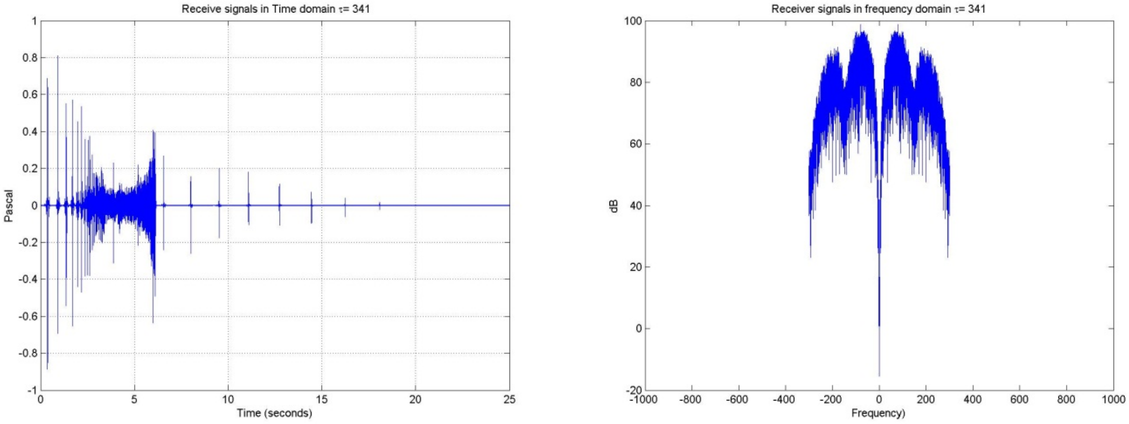
Receiver depth 10 m



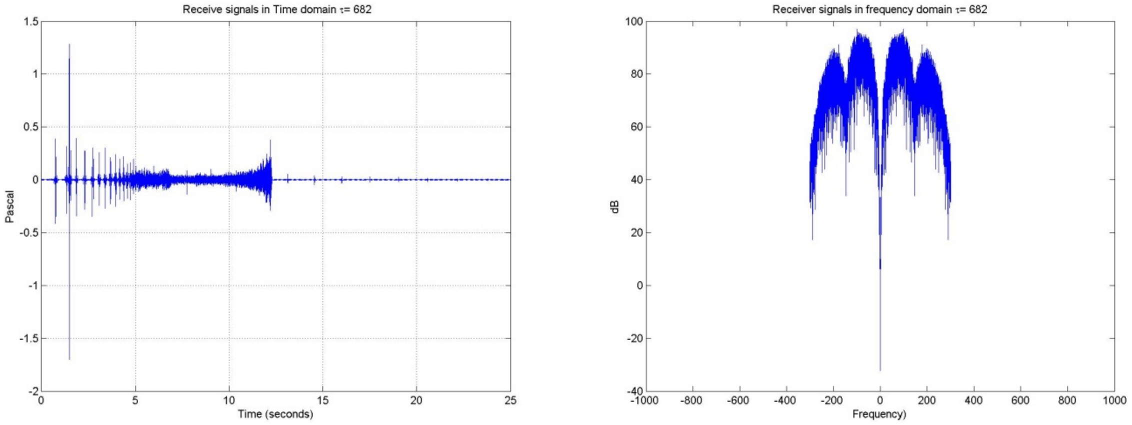
100 km



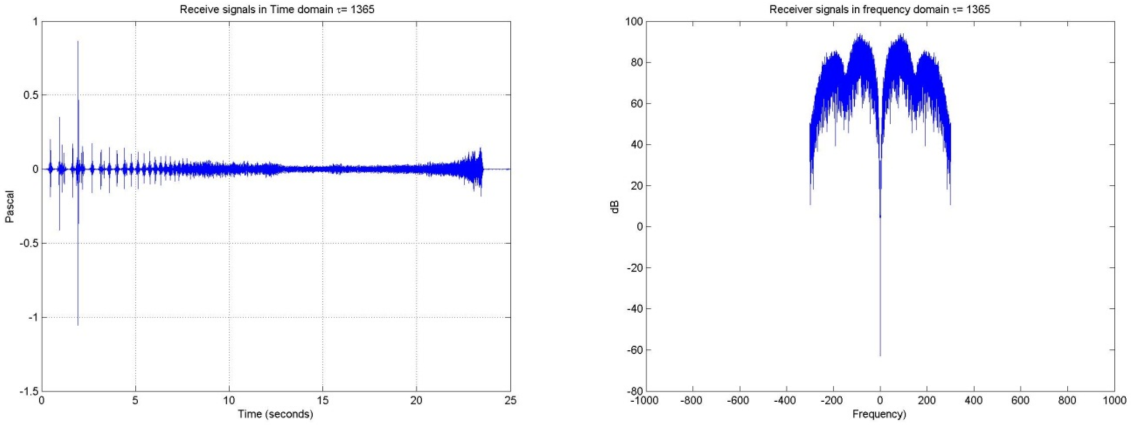
200 km



500 km

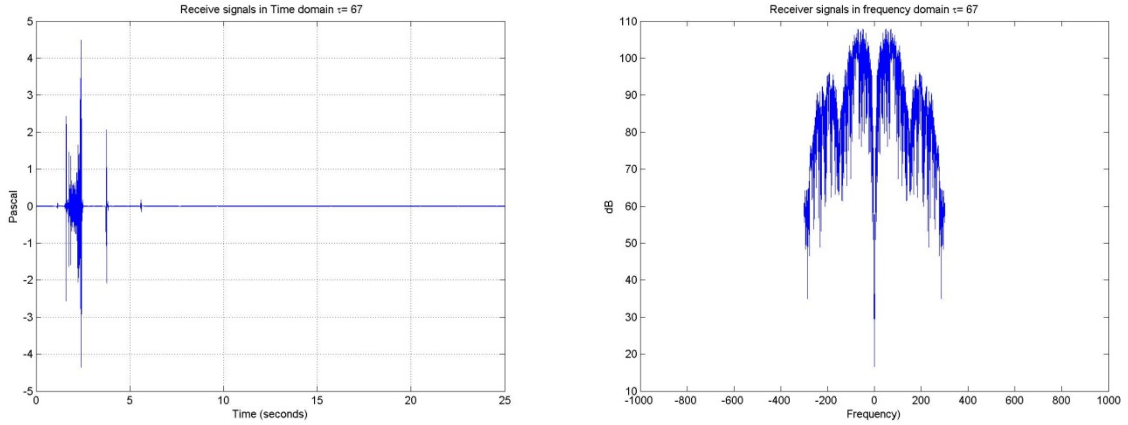


1000 km

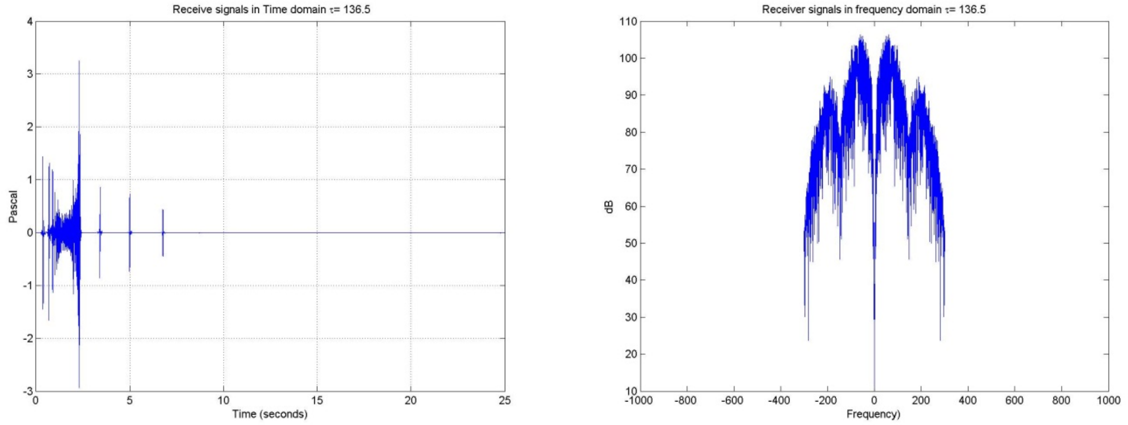


2000 km

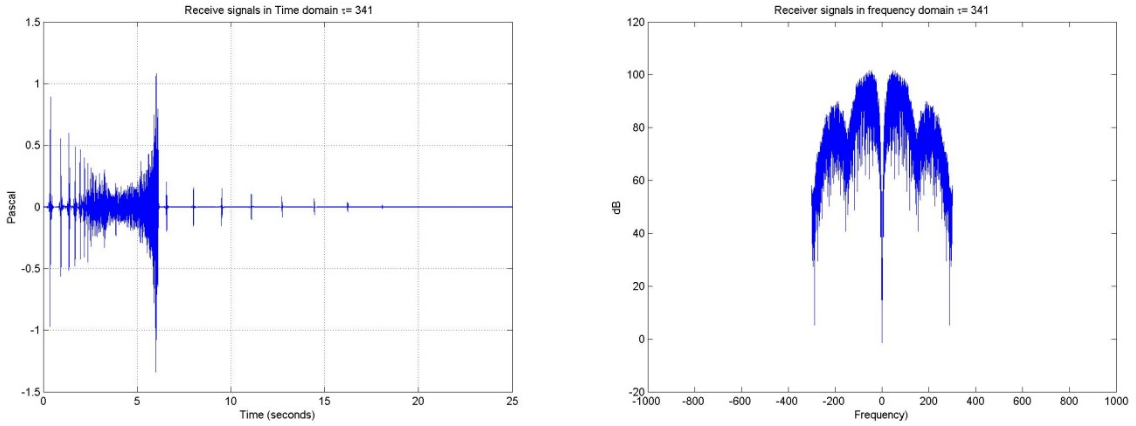
Receiver depth 50 m



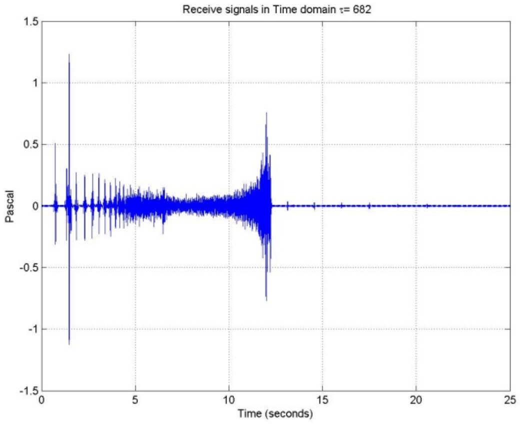
100 km

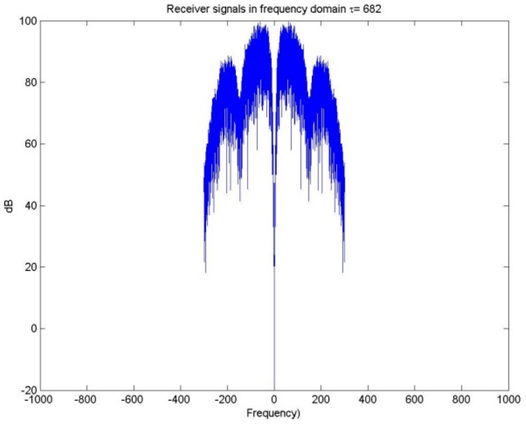


200 km

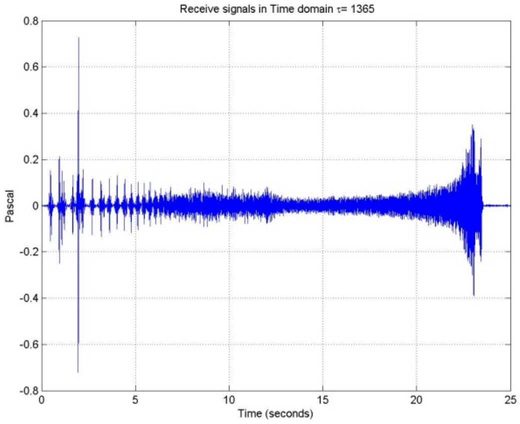


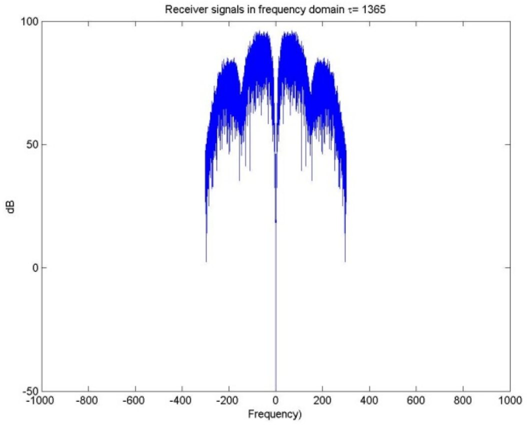
500 km





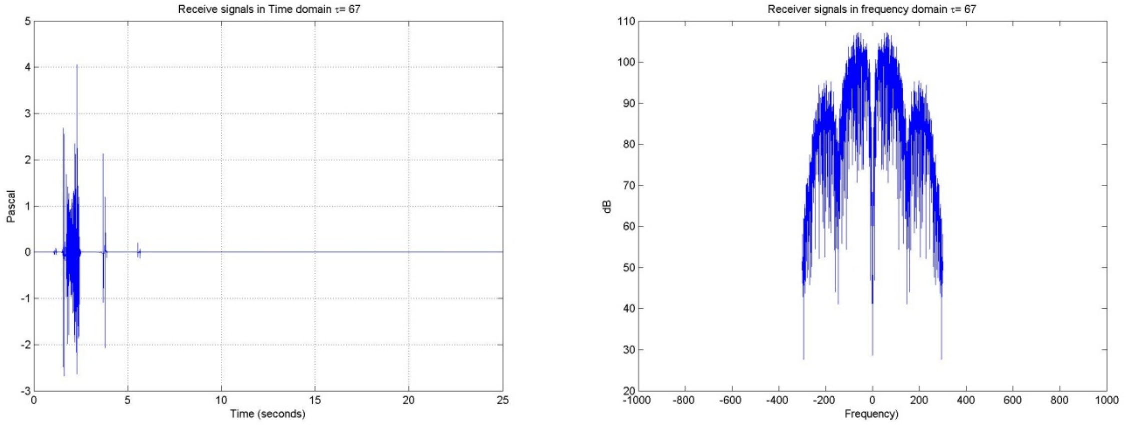
1000 km



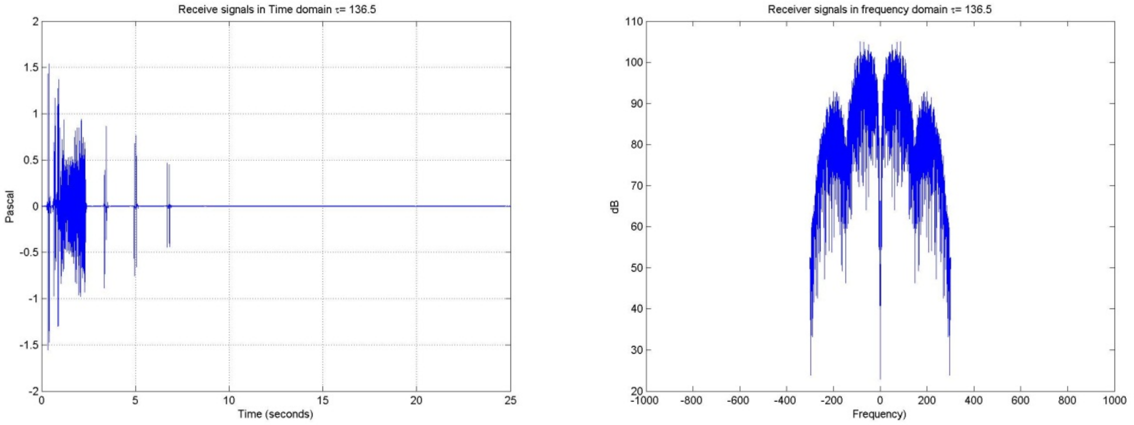


2000 km

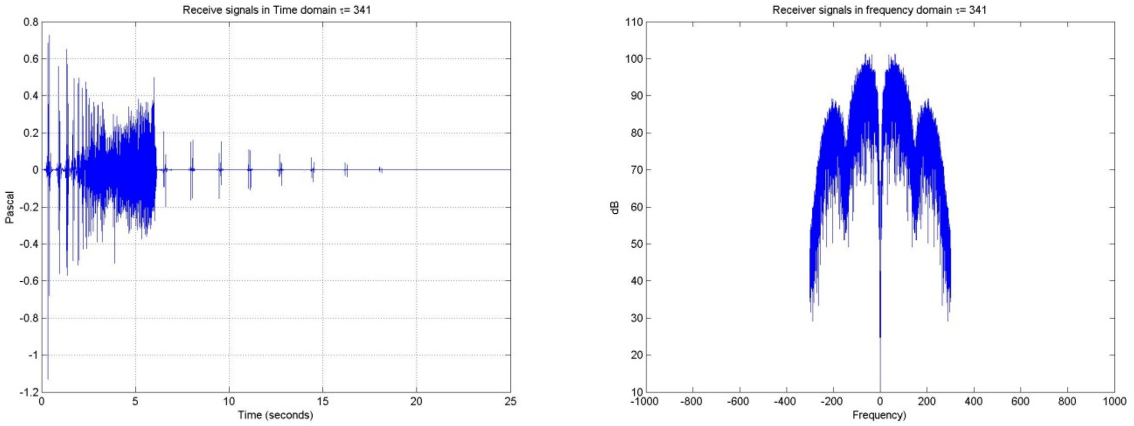
Receiver depth 200 m



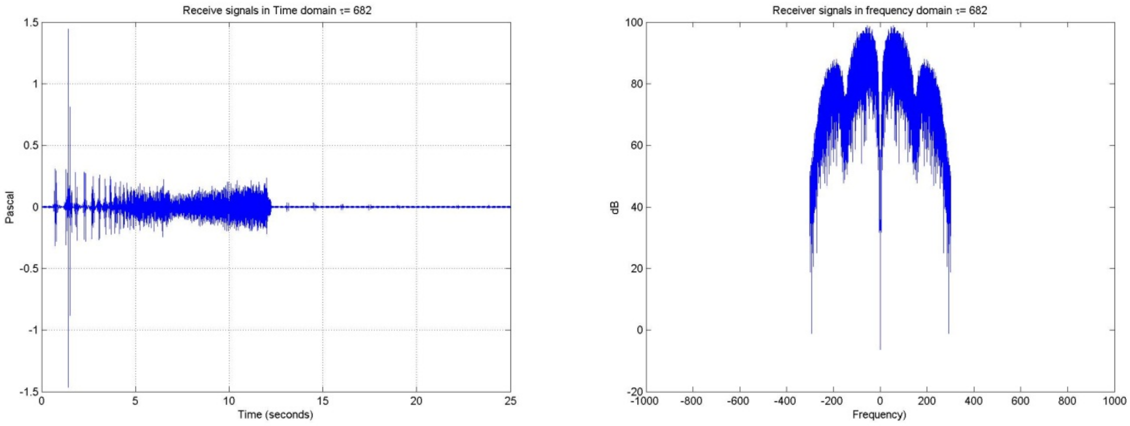
100 km



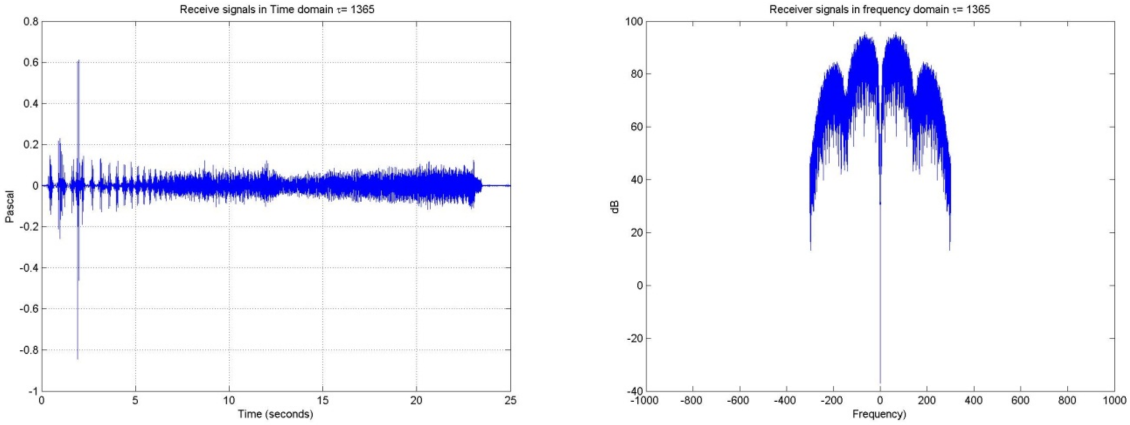
200 km



500 km



1000 km

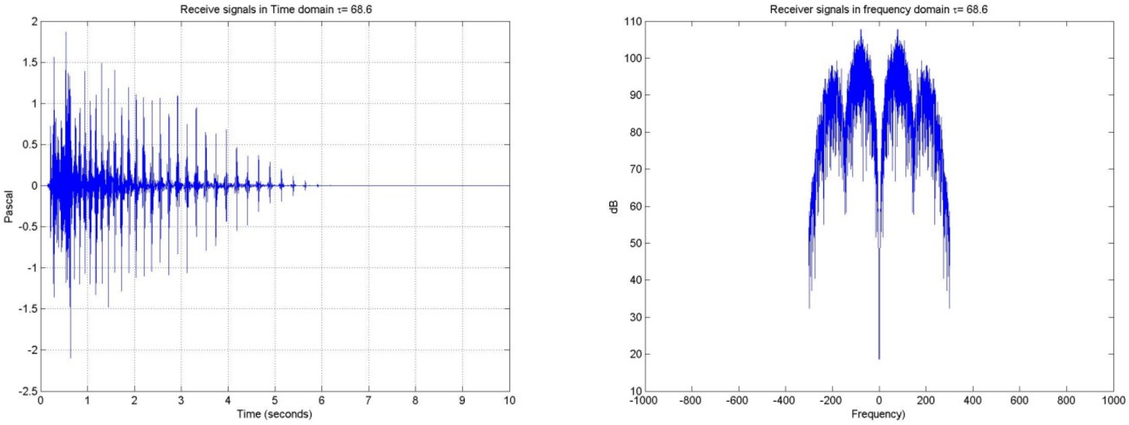


2000 km

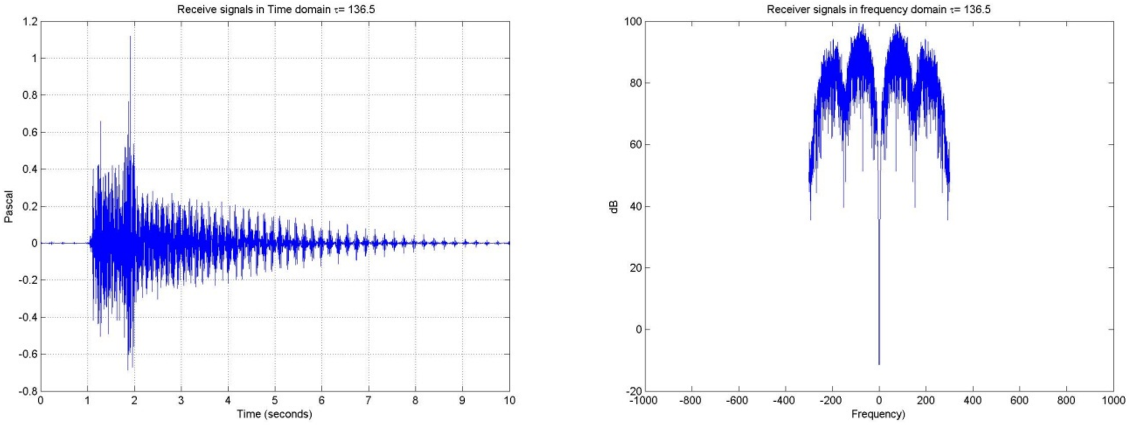
11.4.2 Depth 500 m

11.4.2.1 Station 715

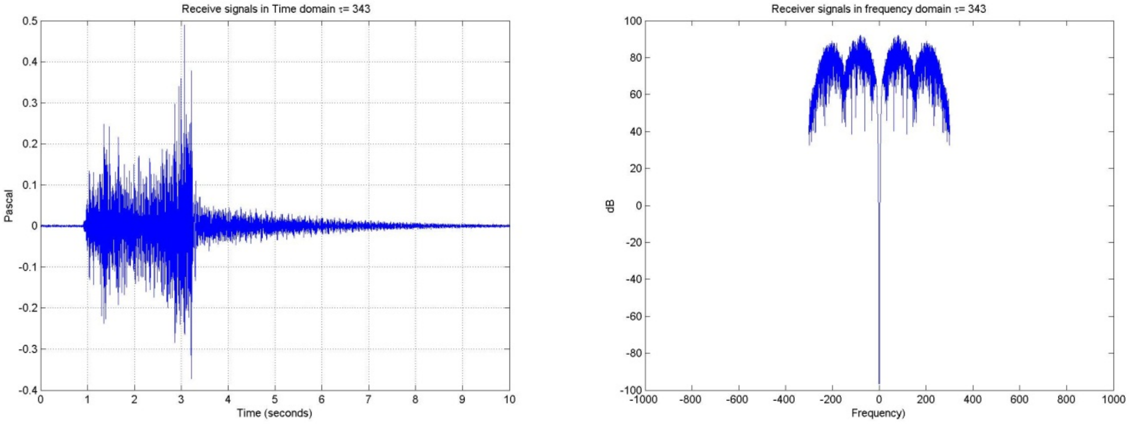
Receiver depth 10 m



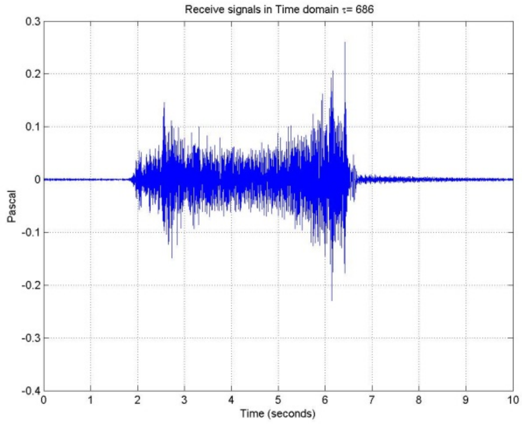
100 km

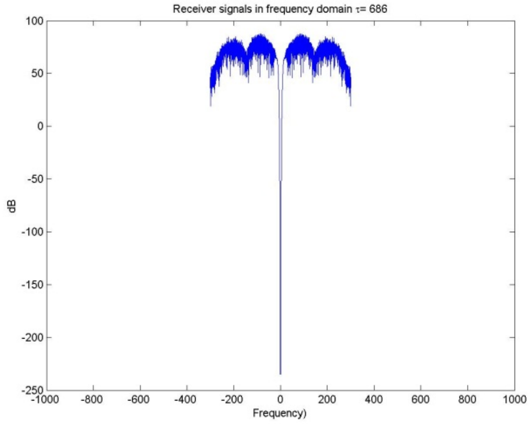


200 km

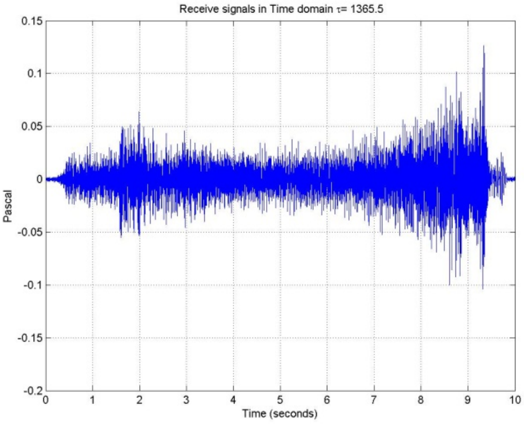


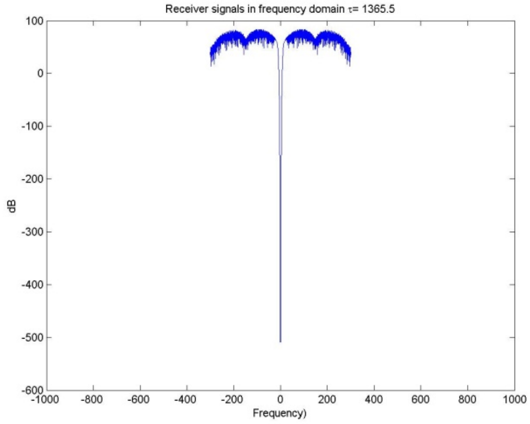
500 km





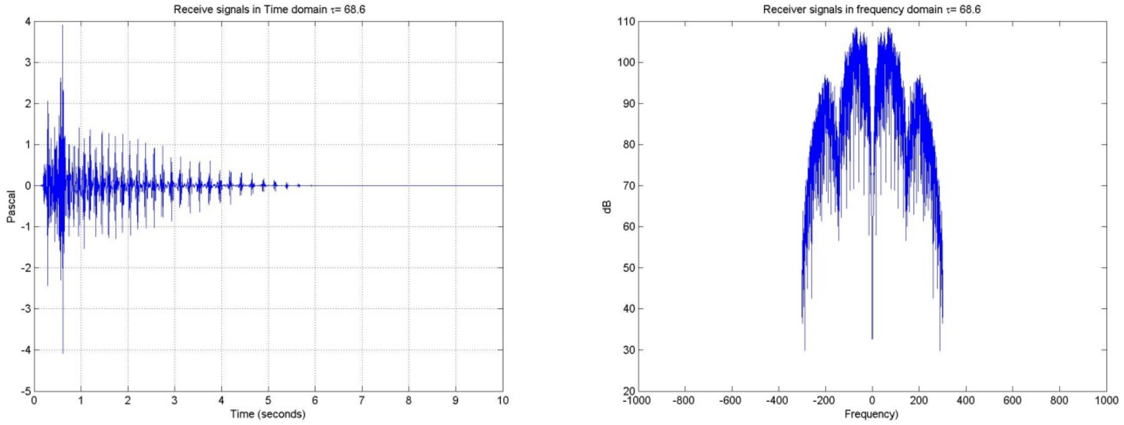
1000 km



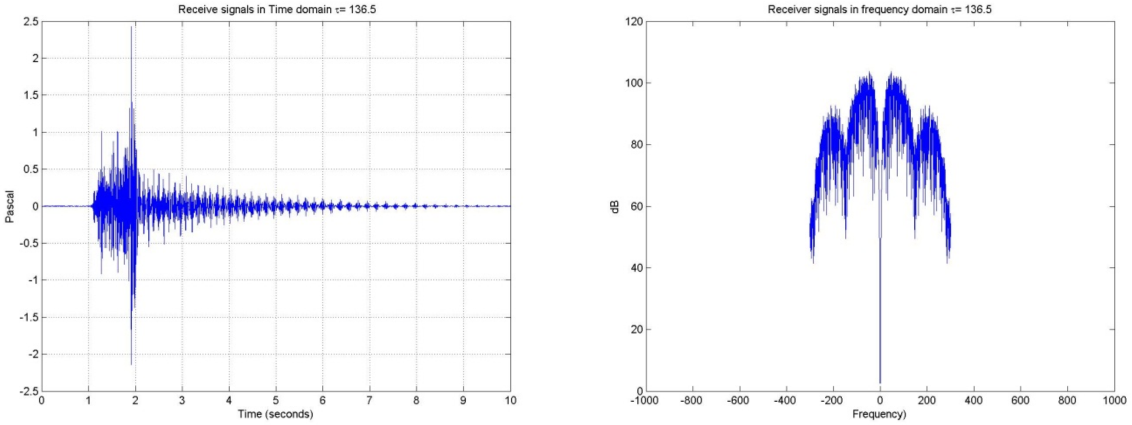


2000 km

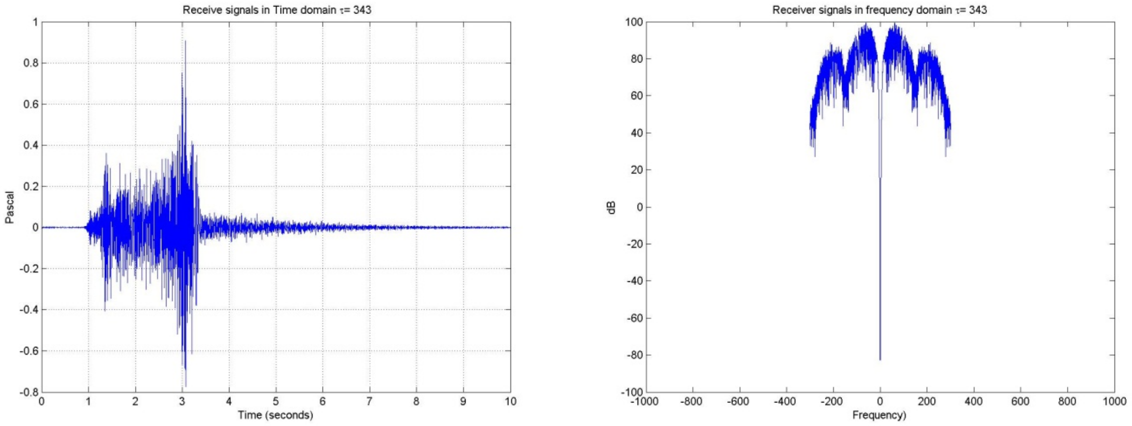
Receiver depth 50 m



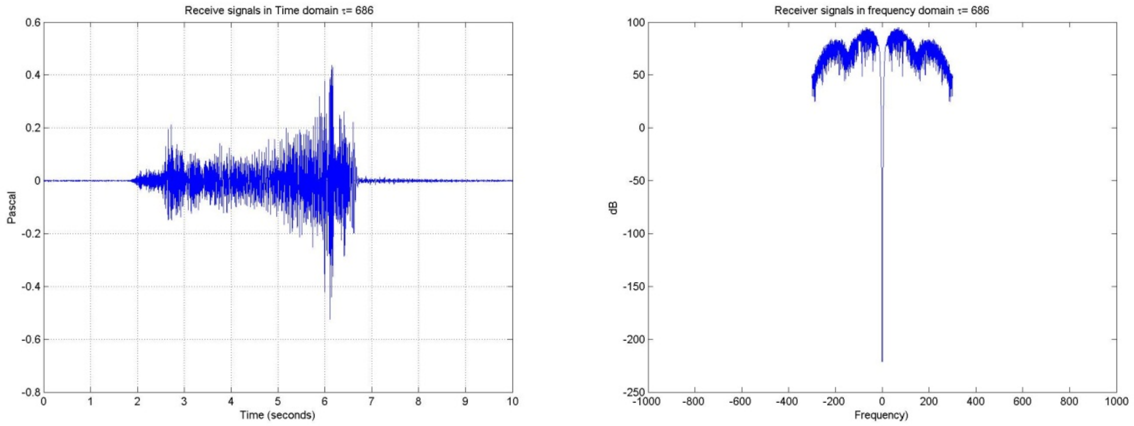
100 km



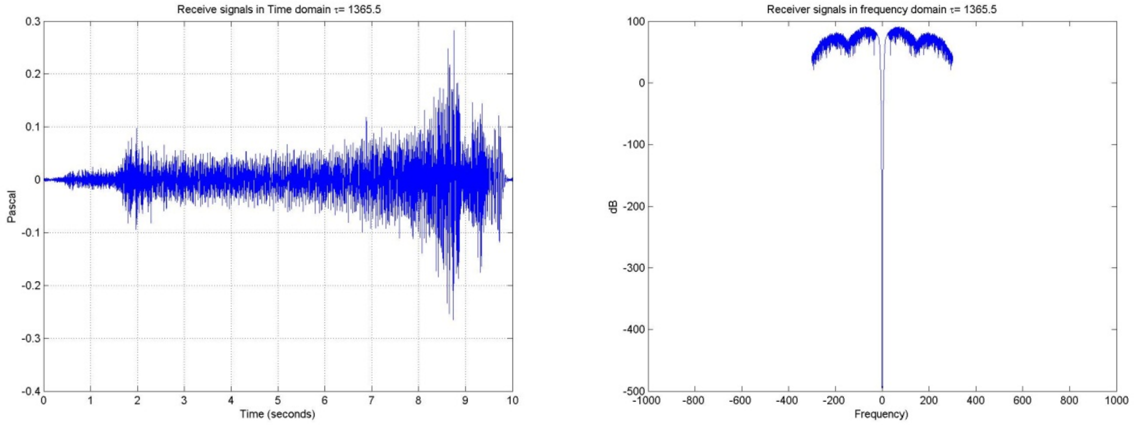
200 km



500 km

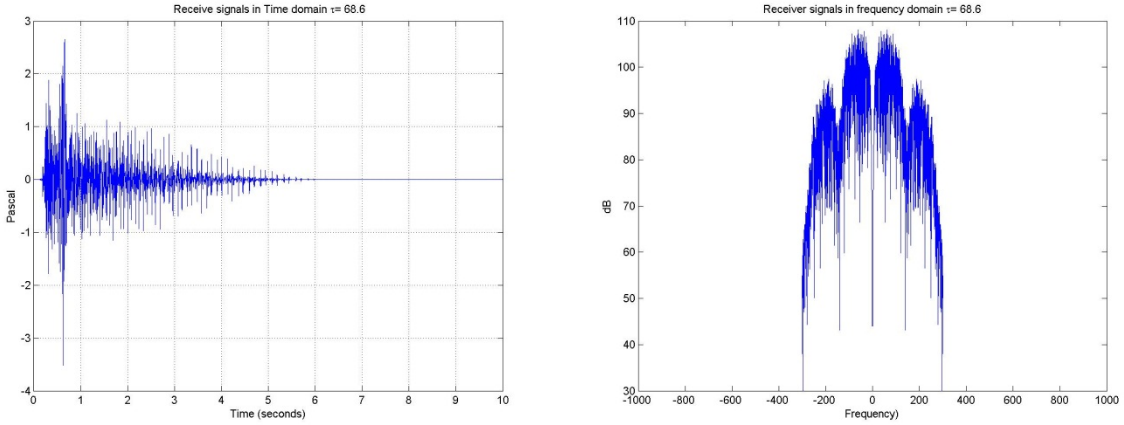


1000 km

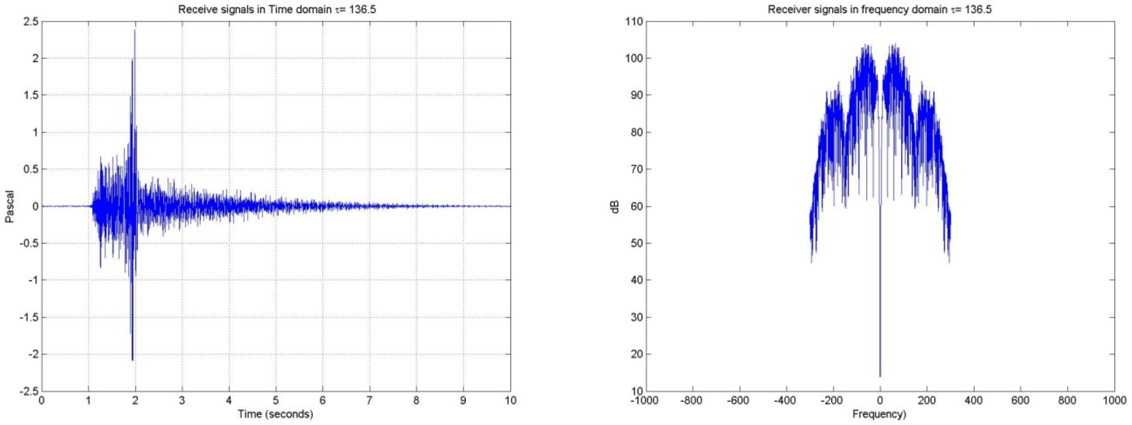


2000 km

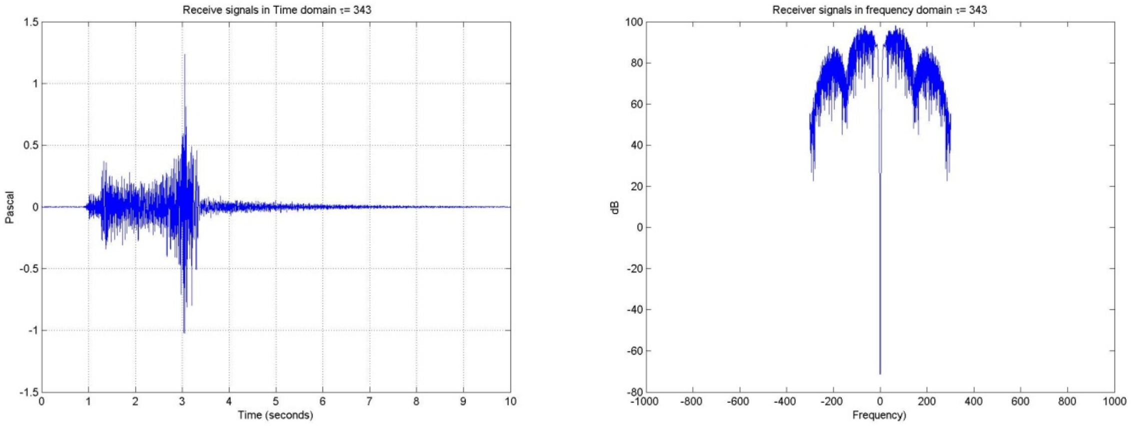
Receiver depth 200 m



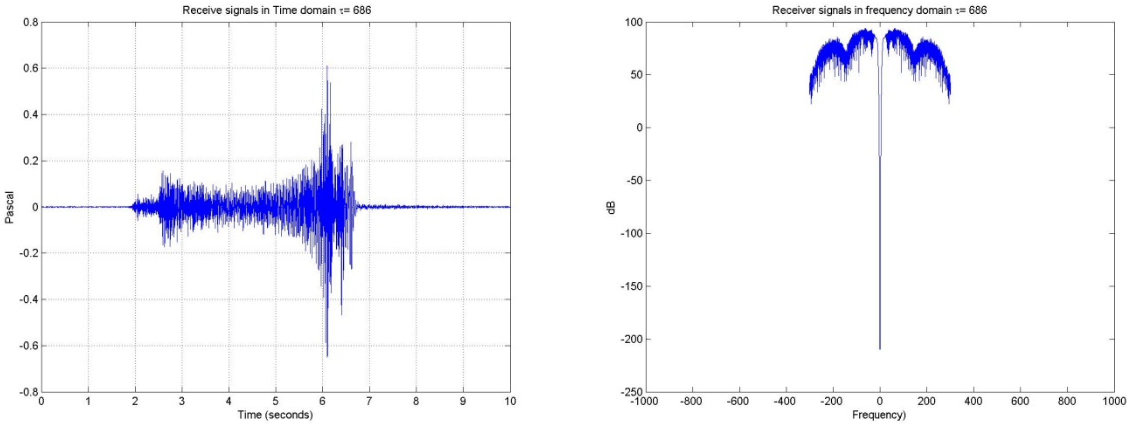
100 km



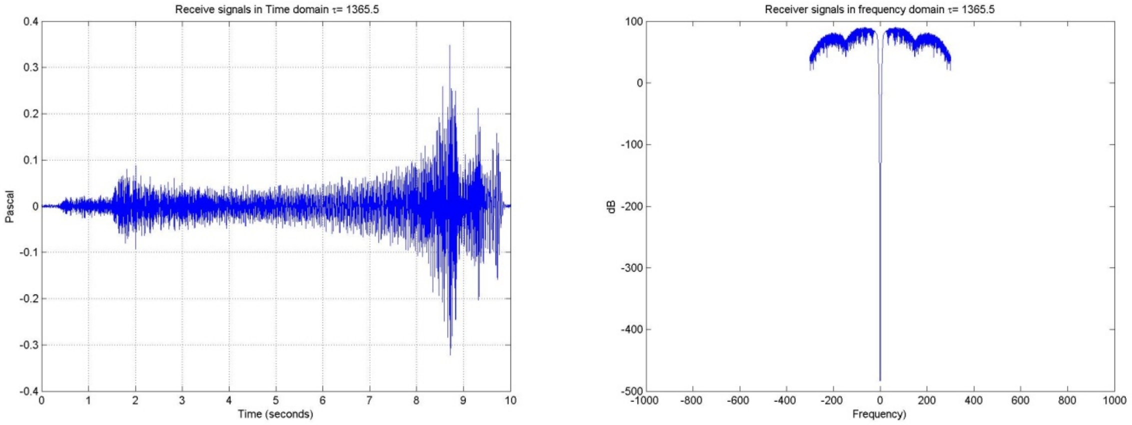
200 km



500 km


Receive signals in Time domain τ= 686
Receiver signals in frequency domain τ= 686

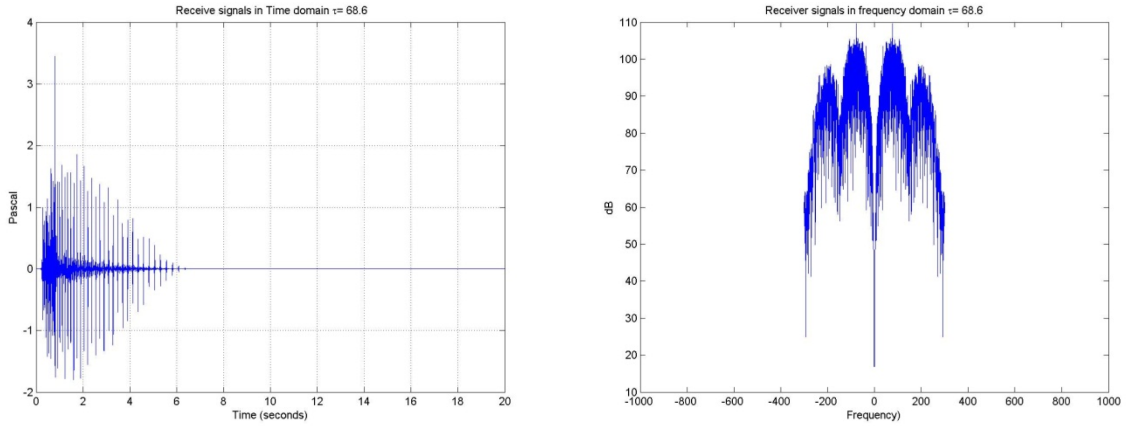
1000 km


Receive signals in Time domain τ= 1365.5
Receiver signals in frequency domain τ= 1365.5

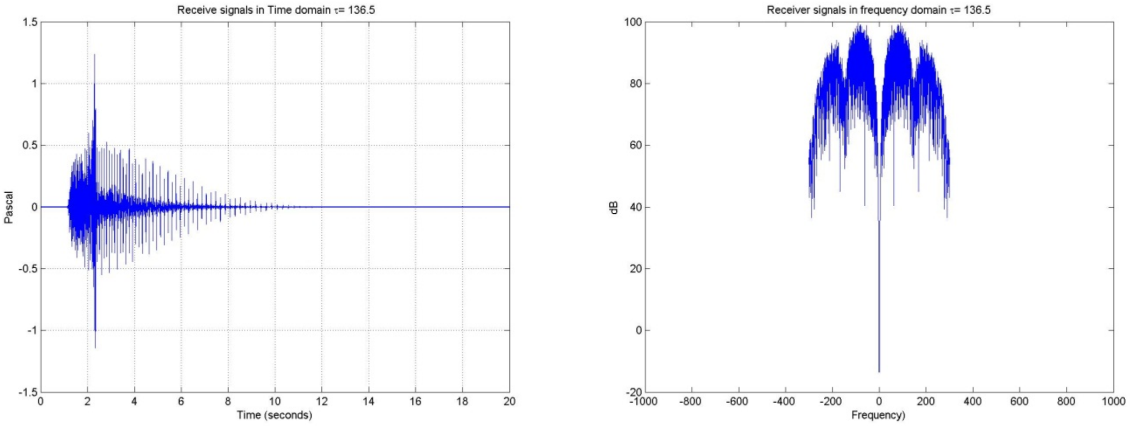
2000 km

11.4.2.2 Station 25

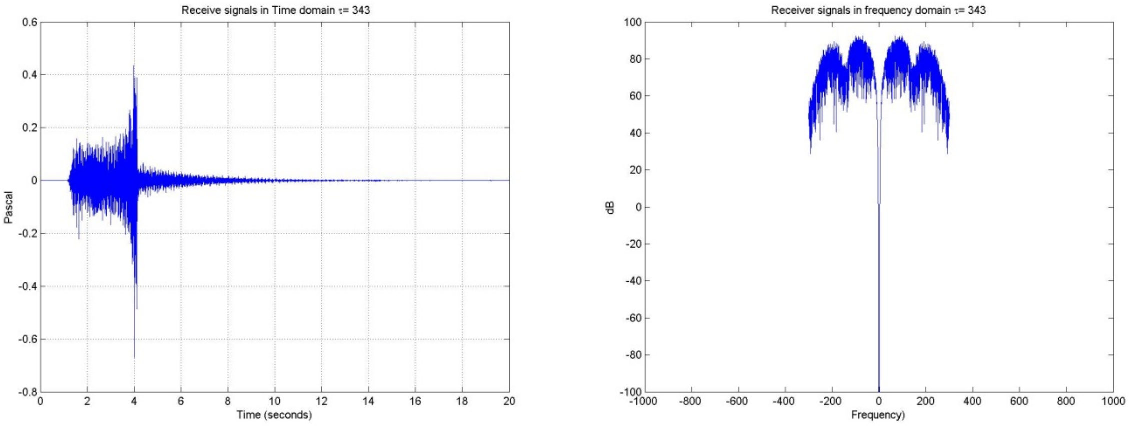
Receiver depth 10 m



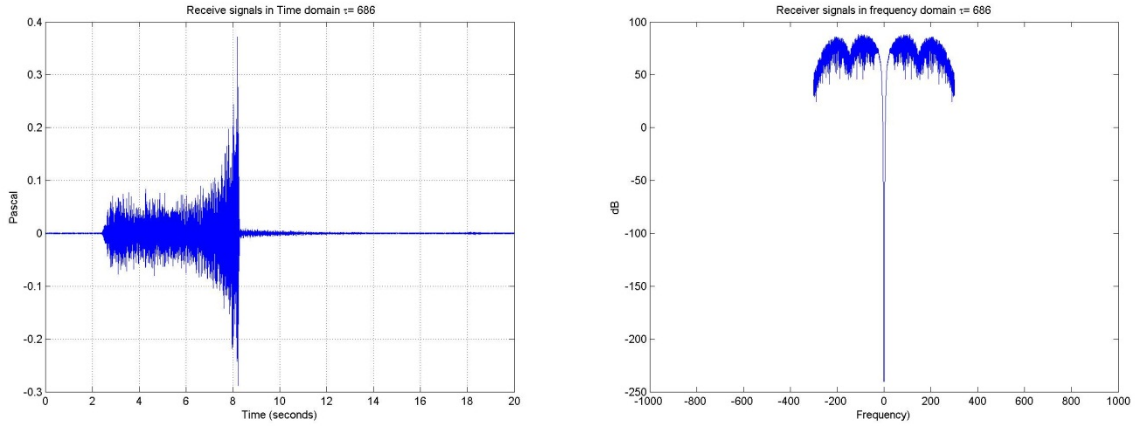
100 km



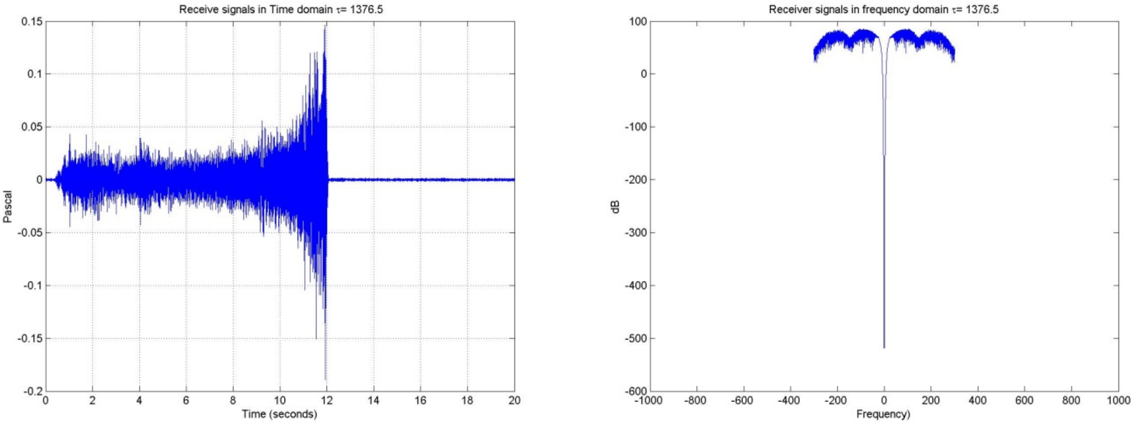
200 km



500 km

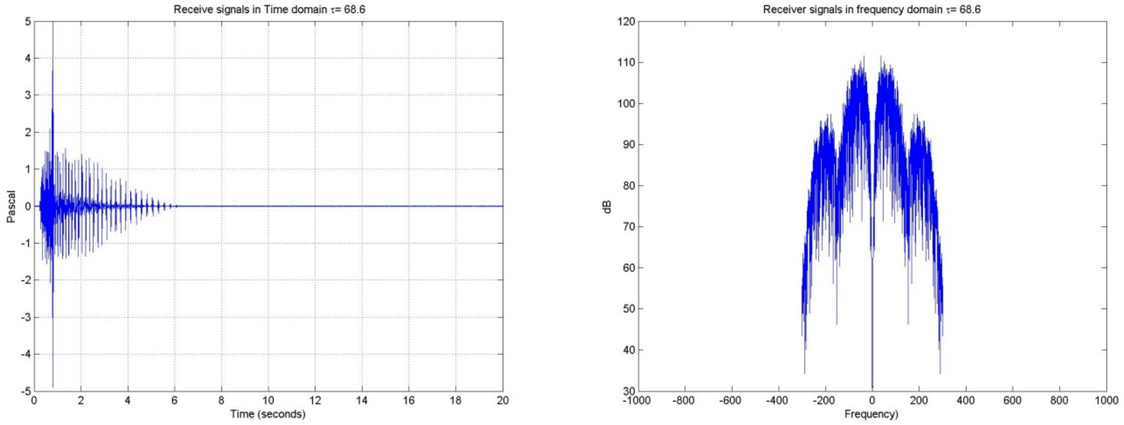


1000 km

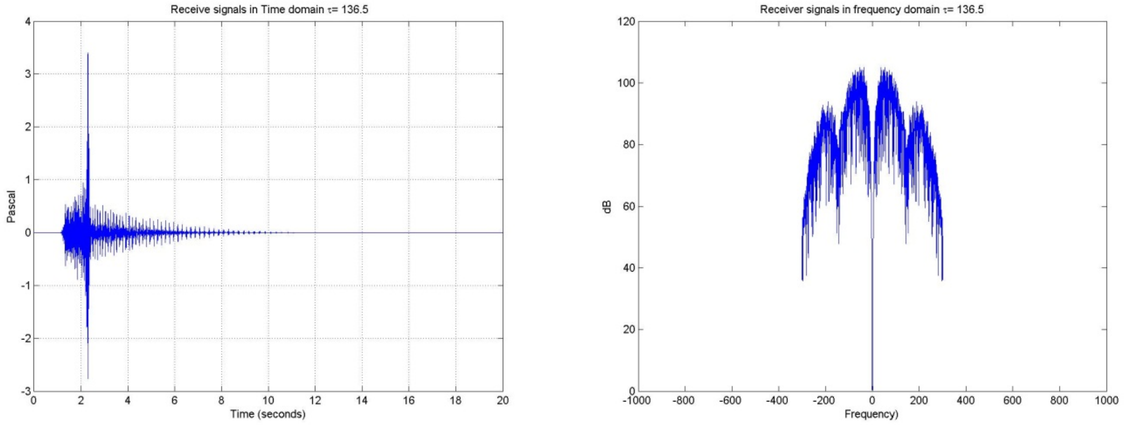


2000 km

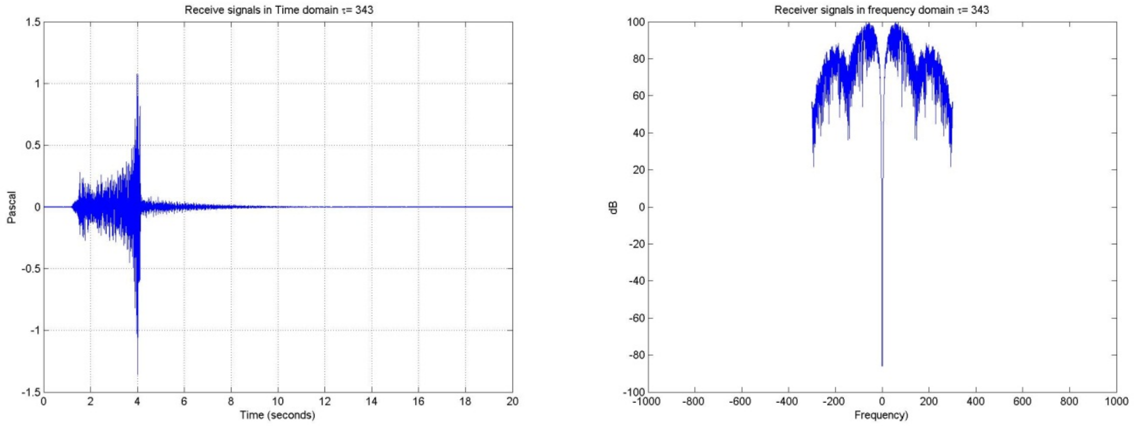
Receiver depth 50 m



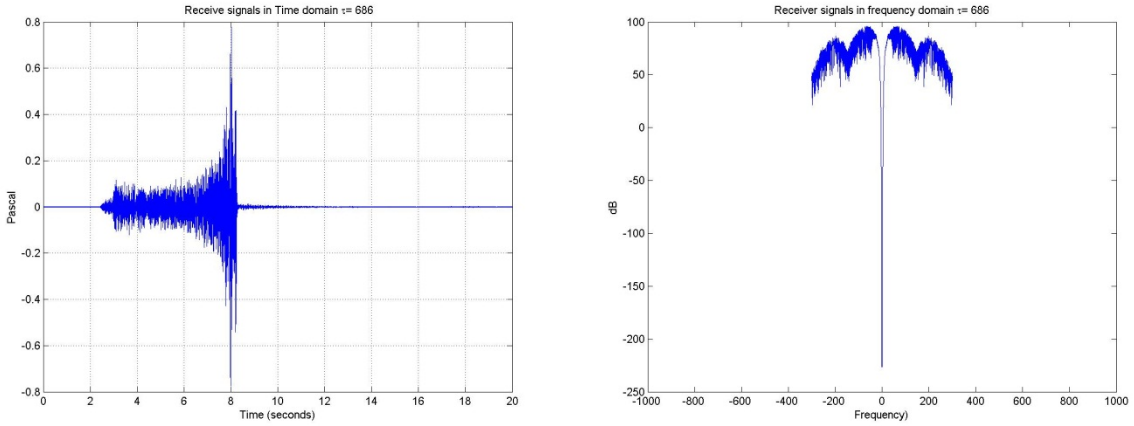
100 km



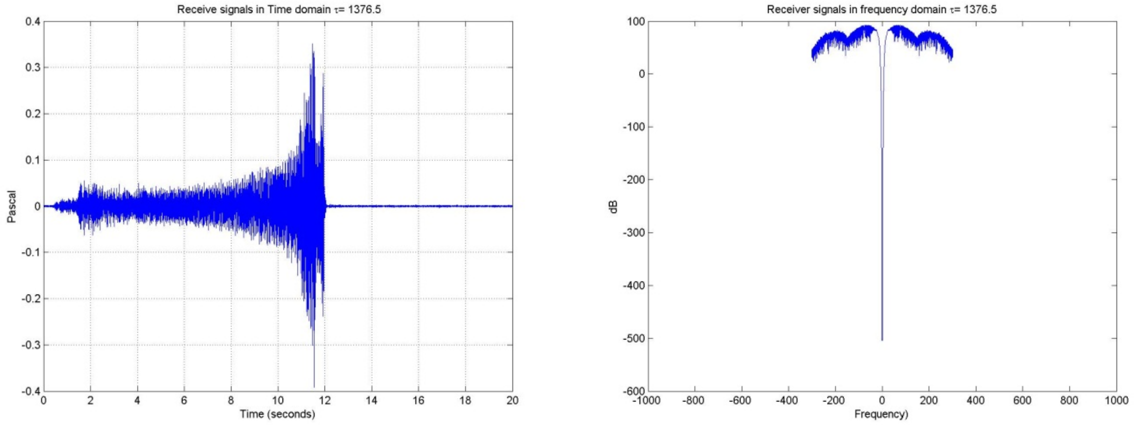
200 km



500 km

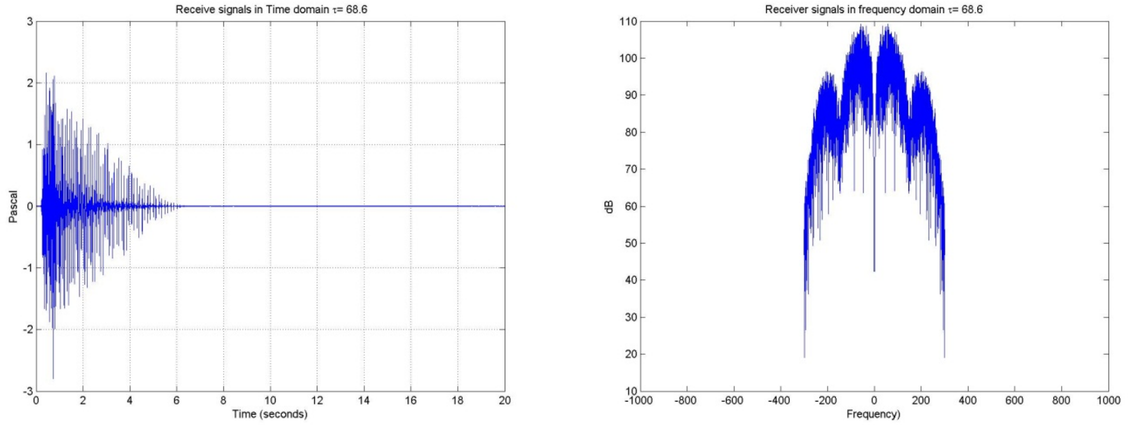


1000 km

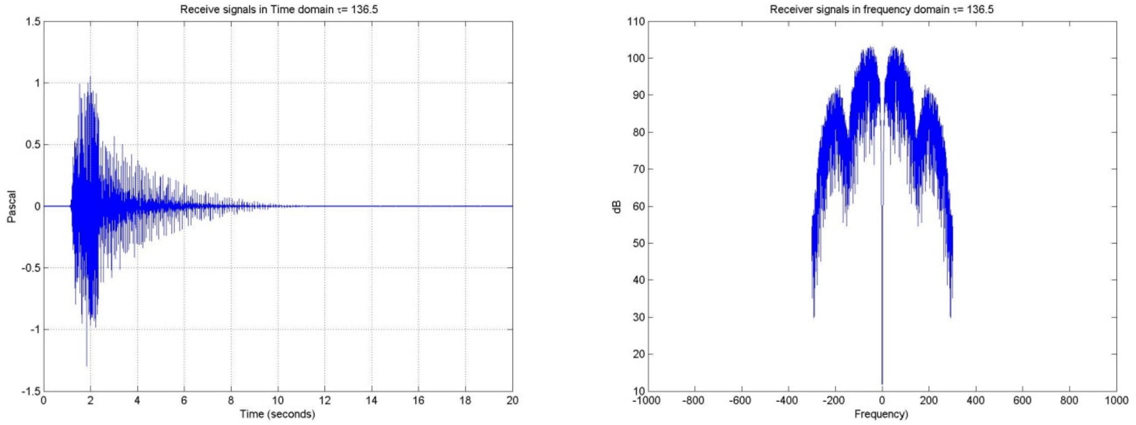


2000 km

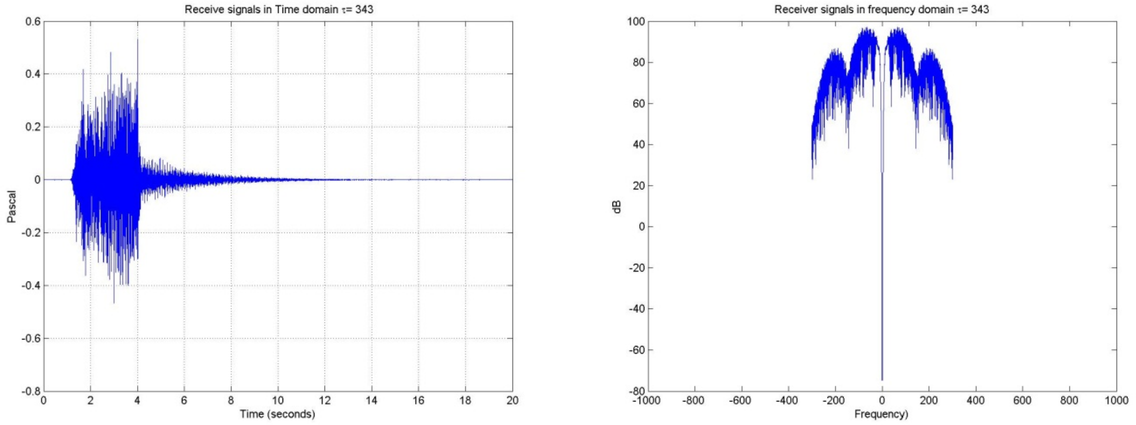
Receiver depth 200 m



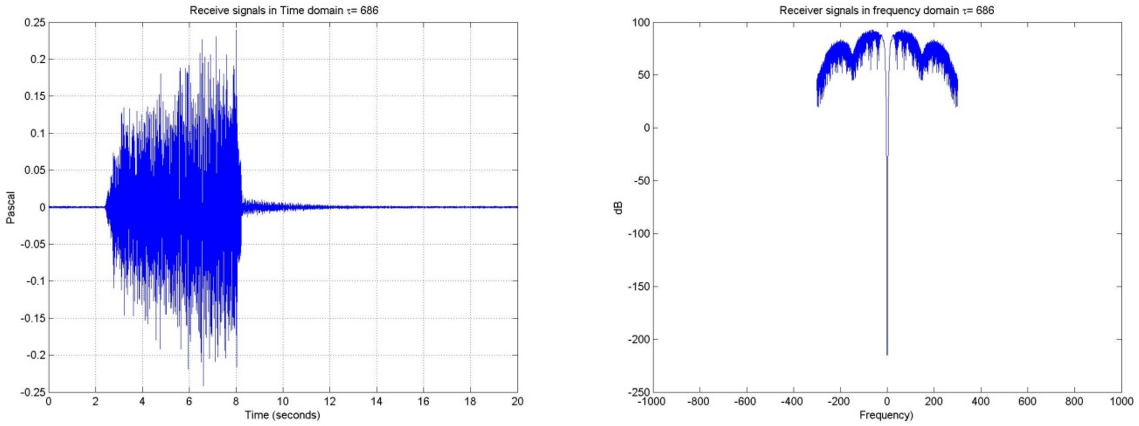
100 km



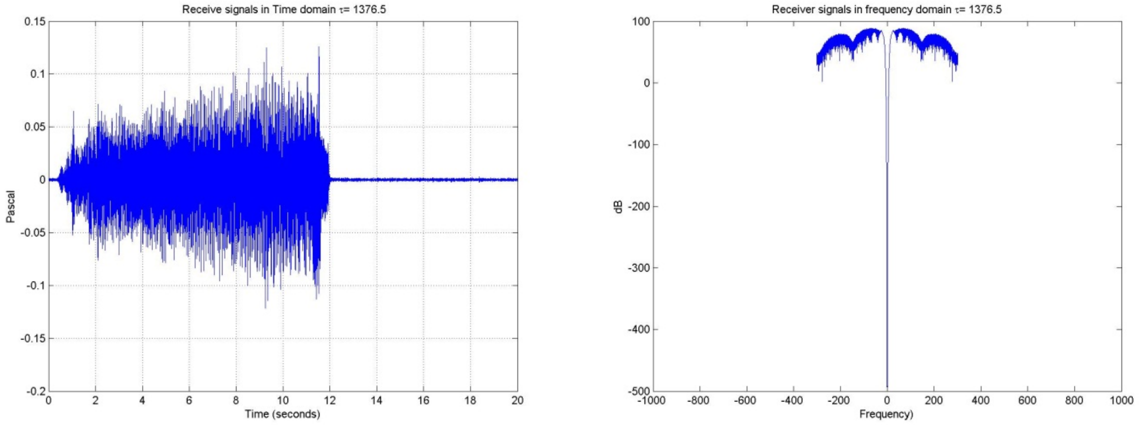
200 km



500 km



1000 km



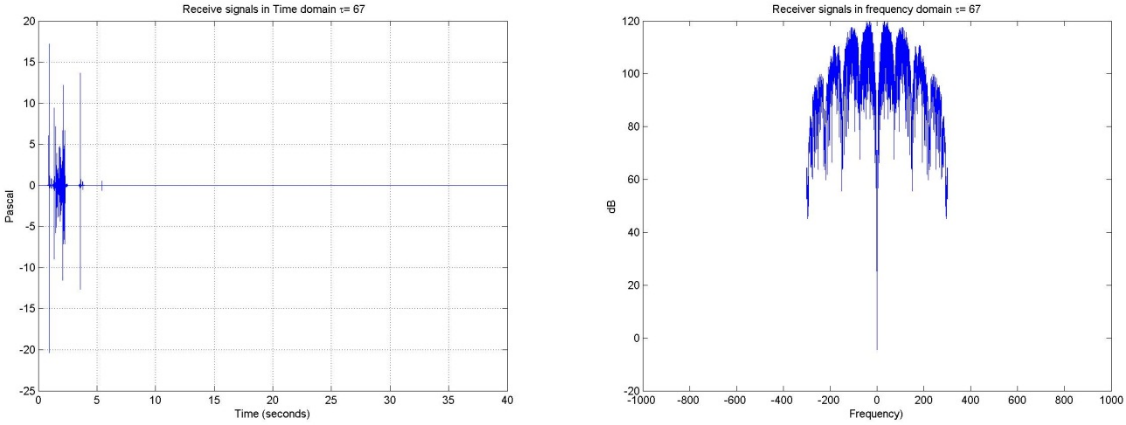
2000 km

11.5 8 G-gun Array, source depth 10 m

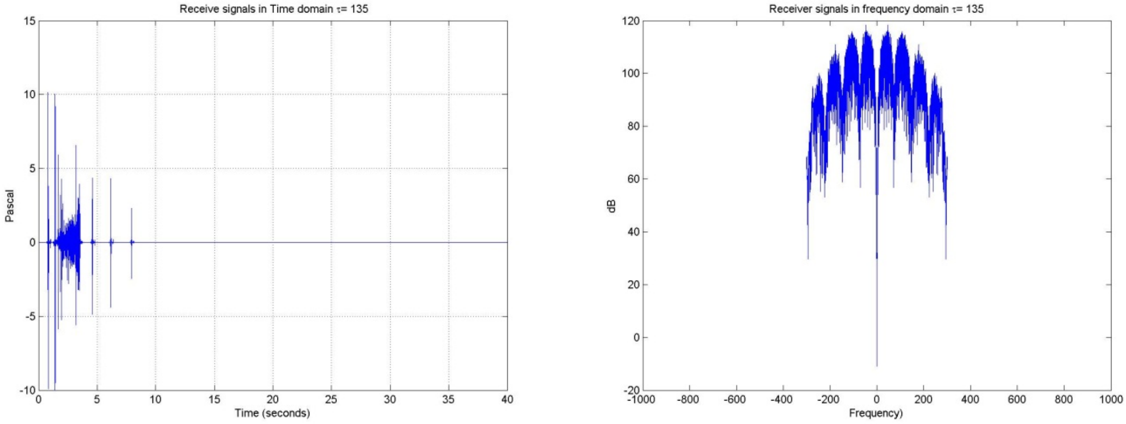
11.5.1 Depth 4000 m

11.5.1.1 Station 715

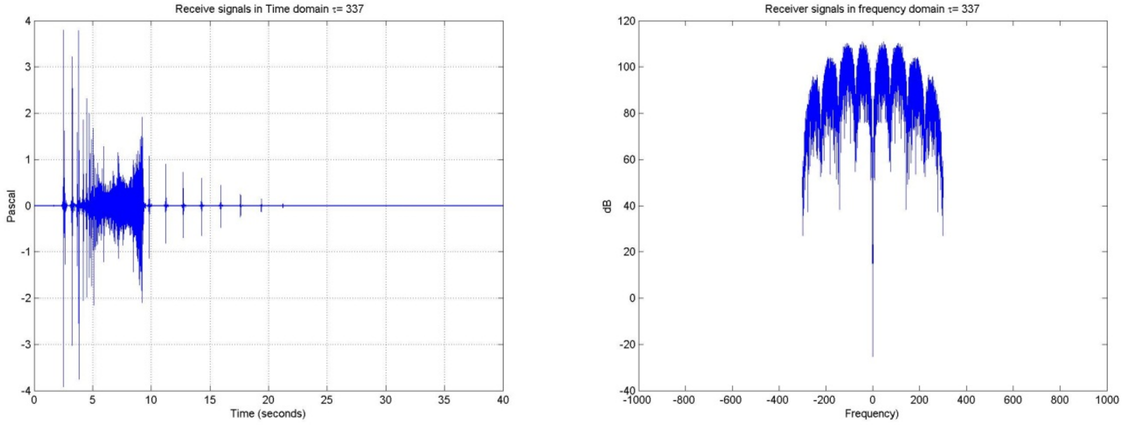
Receiver depth 10 m



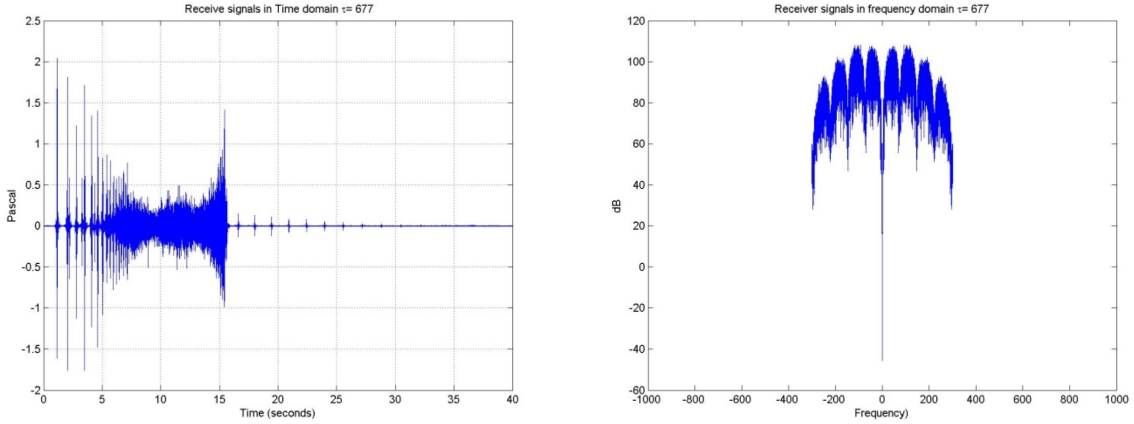
100 km



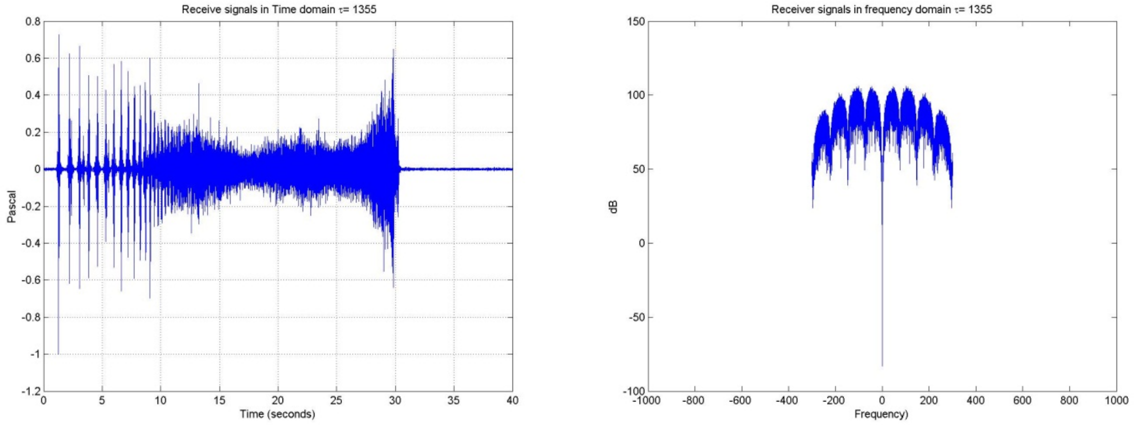
200 km



500 km

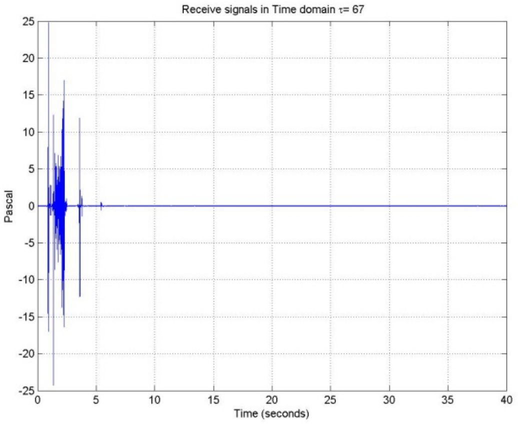


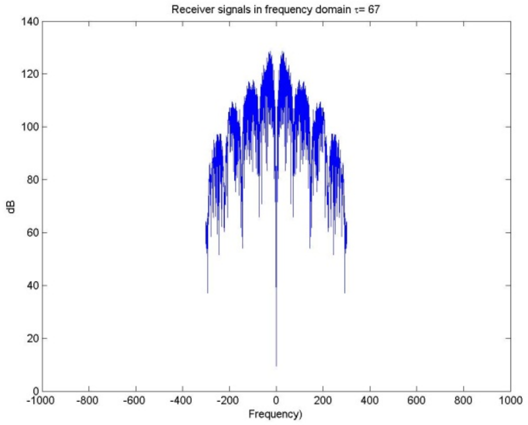
1000 km



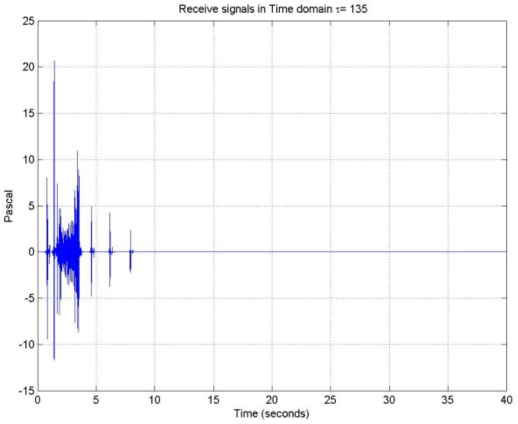
2000 km

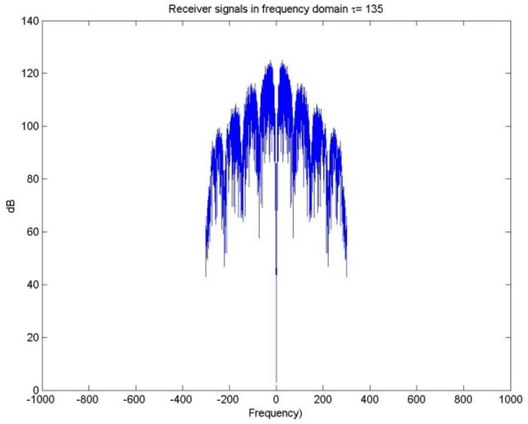
Receiver depth 50 m



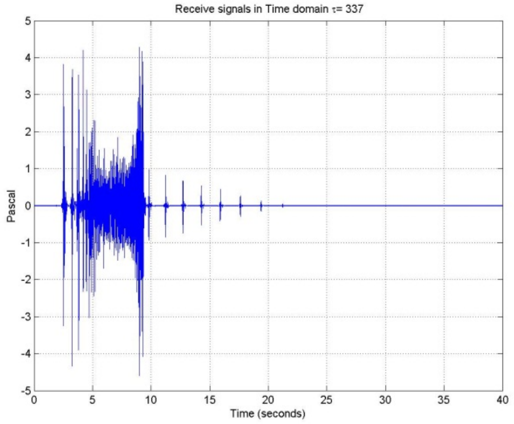


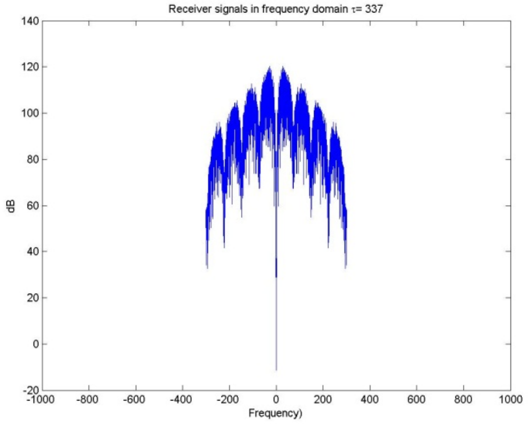
100 km



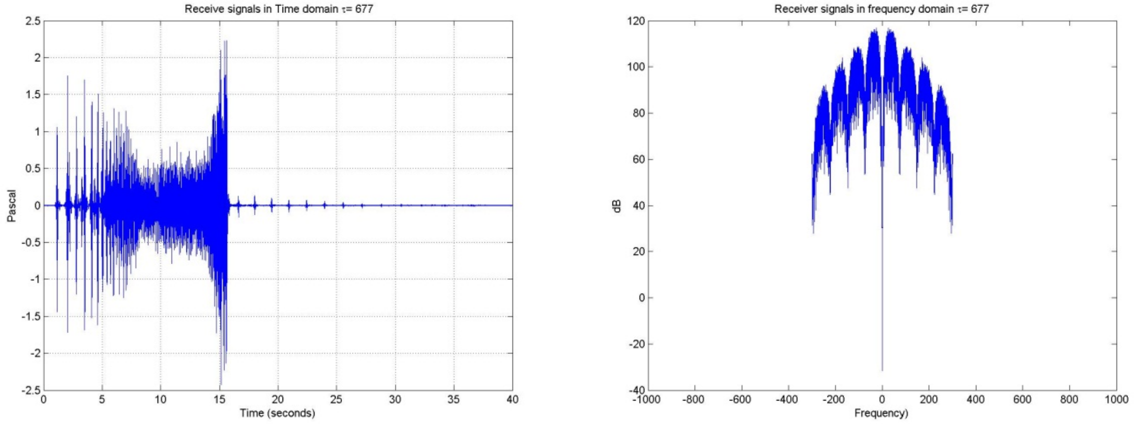


200 km

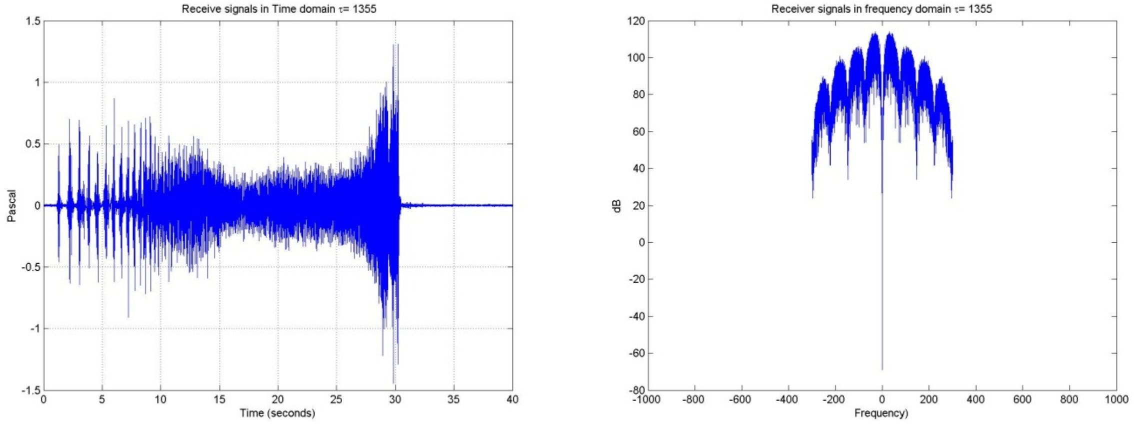




500 km

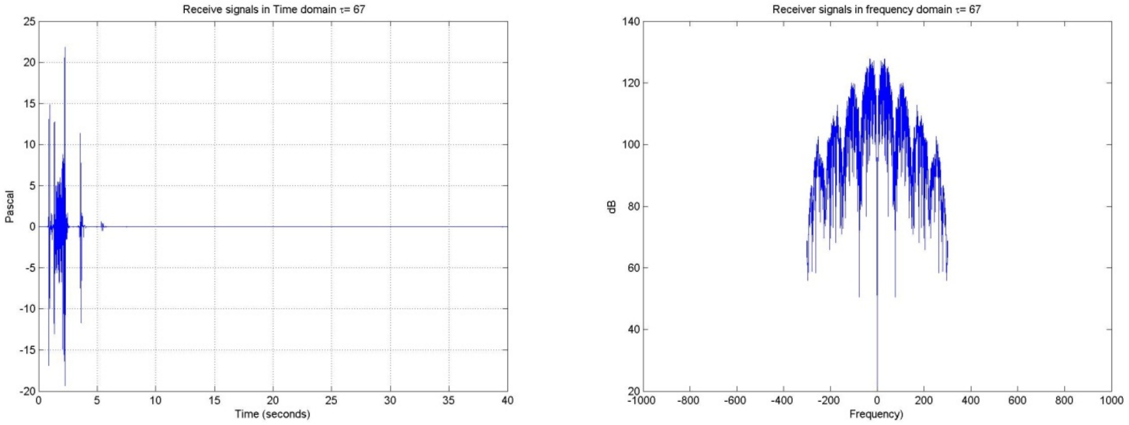


1000 km

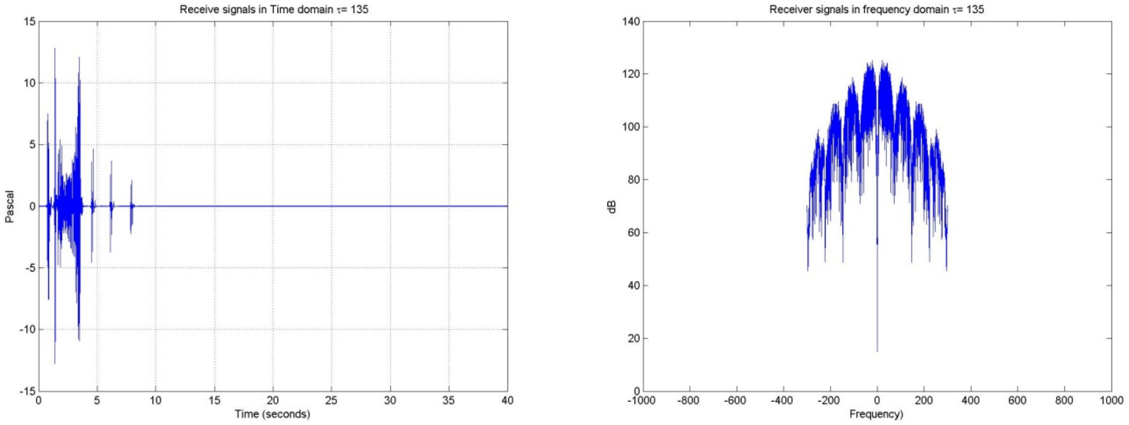


2000 km

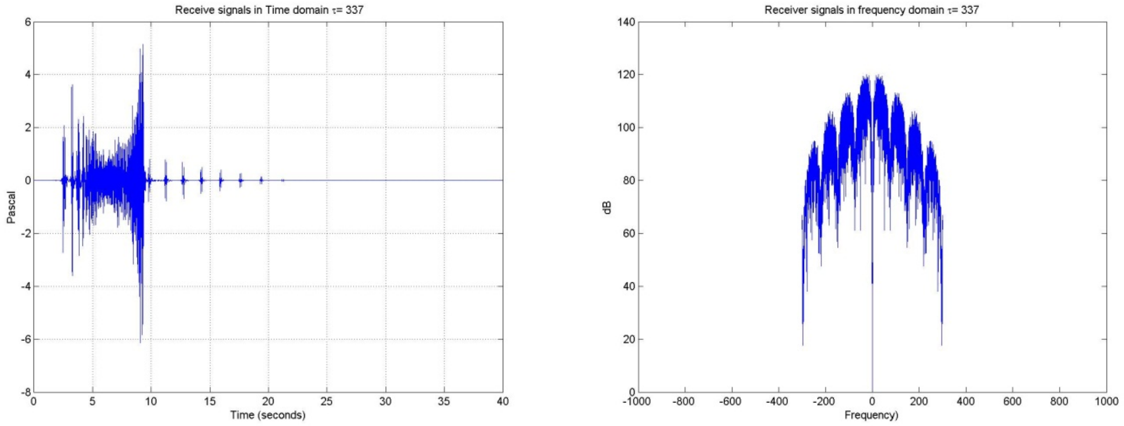
Receiver depth 200 m



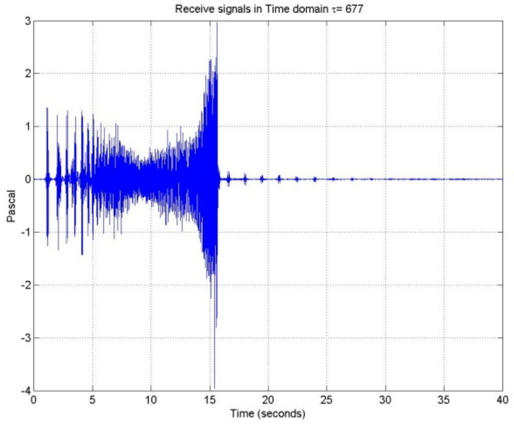
100 km

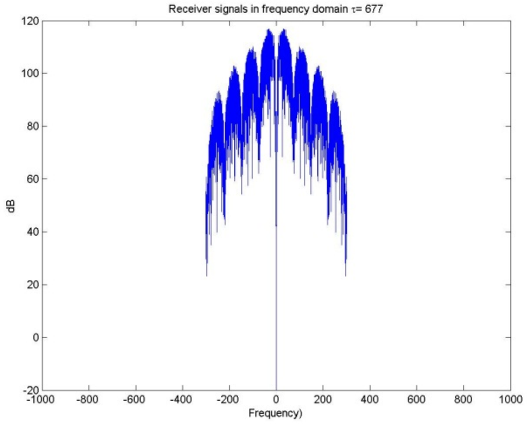


200 km

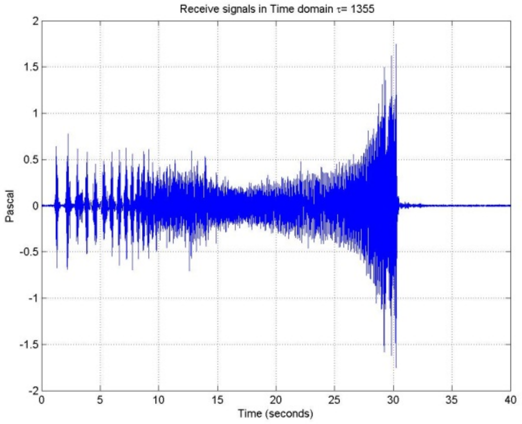


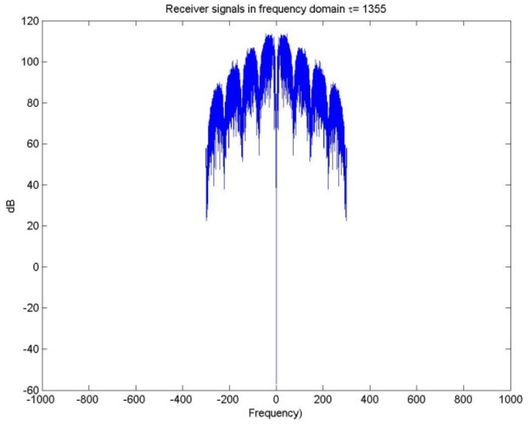
500 km





1000 km

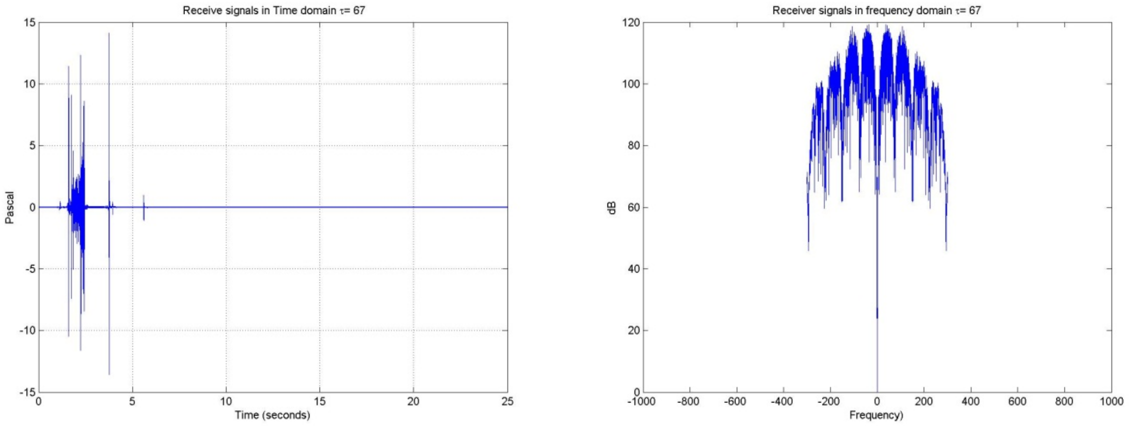




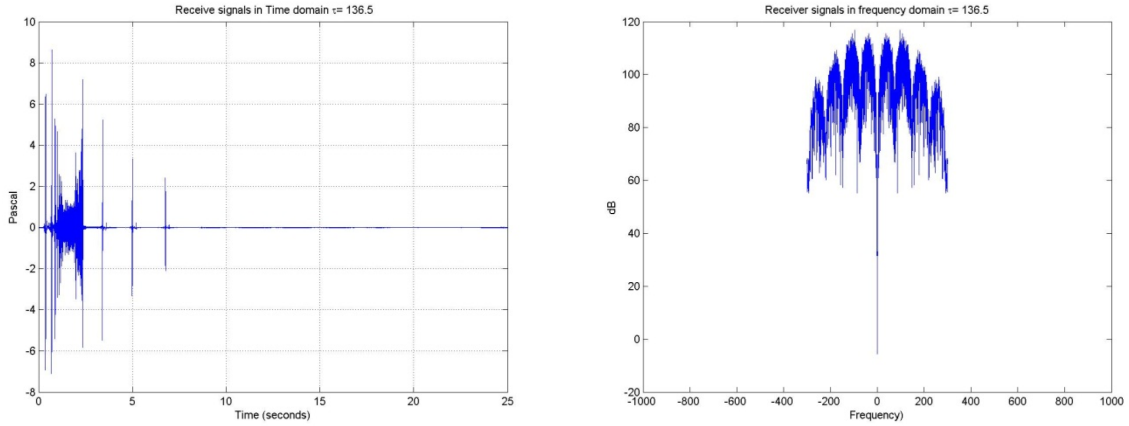
2000 km

11.5.1.2 Station 25

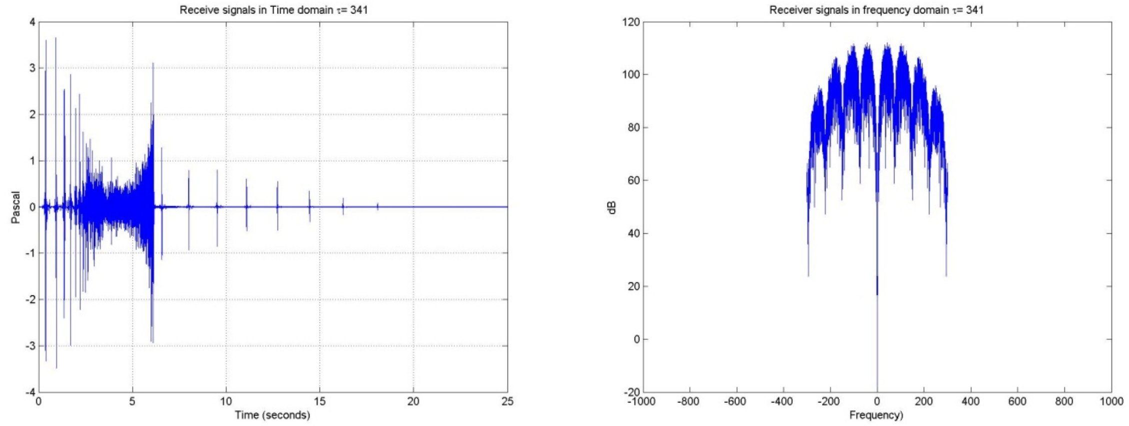
Receiver depth 10 m



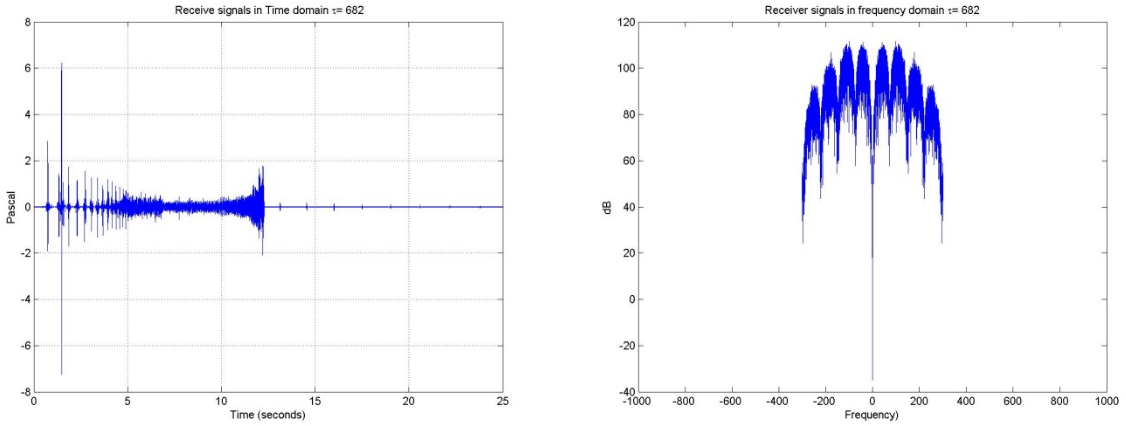
100 km



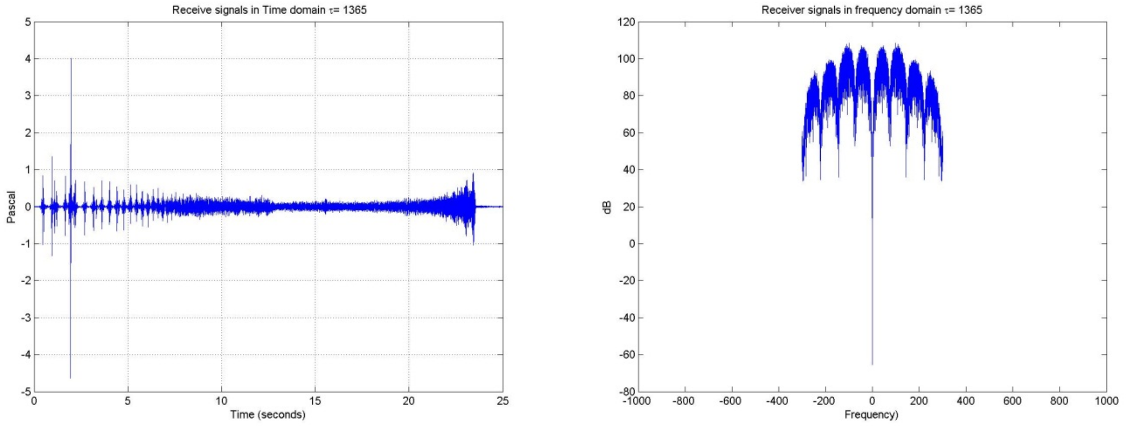
200 km



500 km

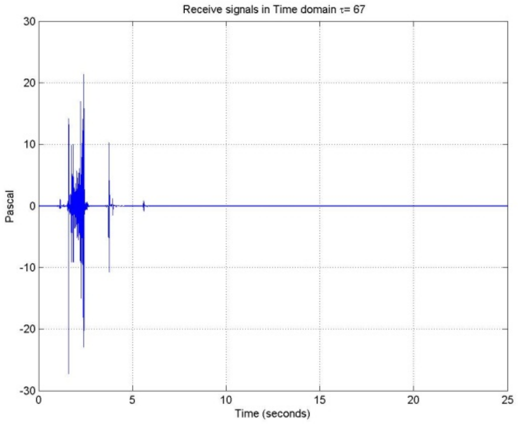


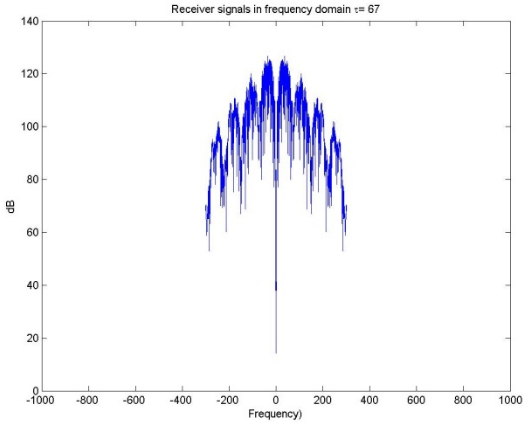
1000 km



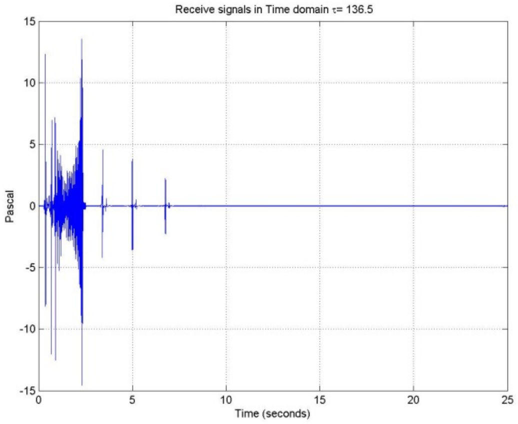
2000 km

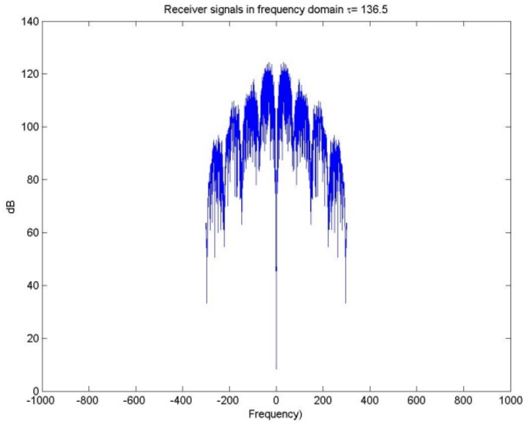
Receiver depth 50 m



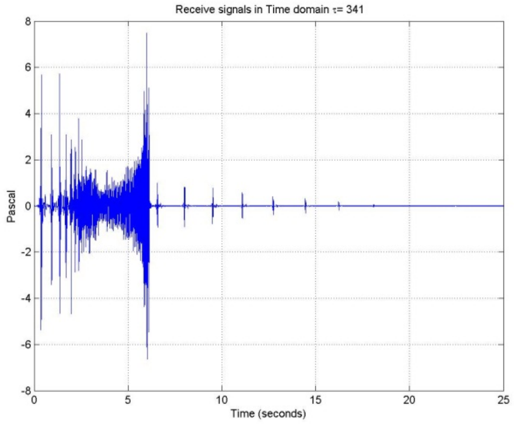


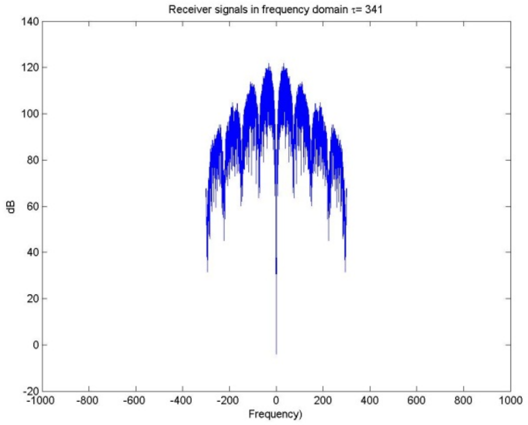
100 km



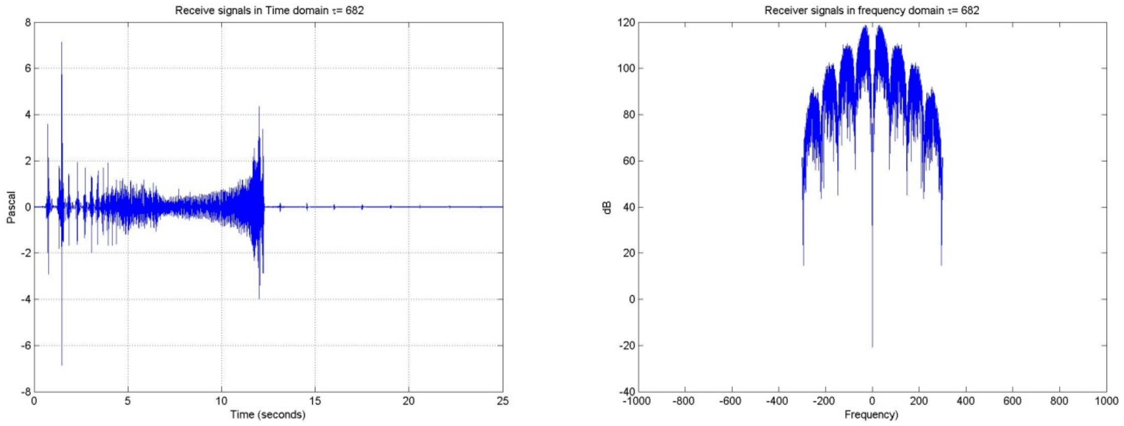


200 km

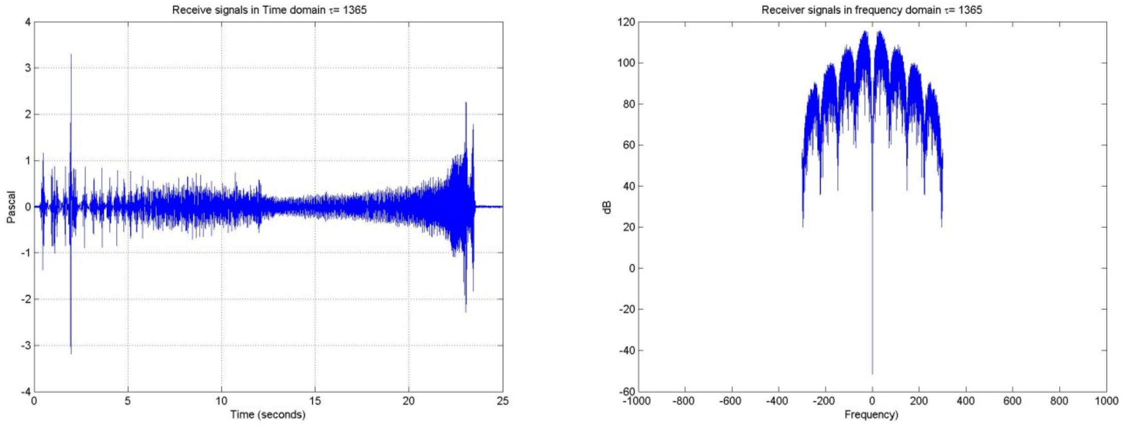




500 km

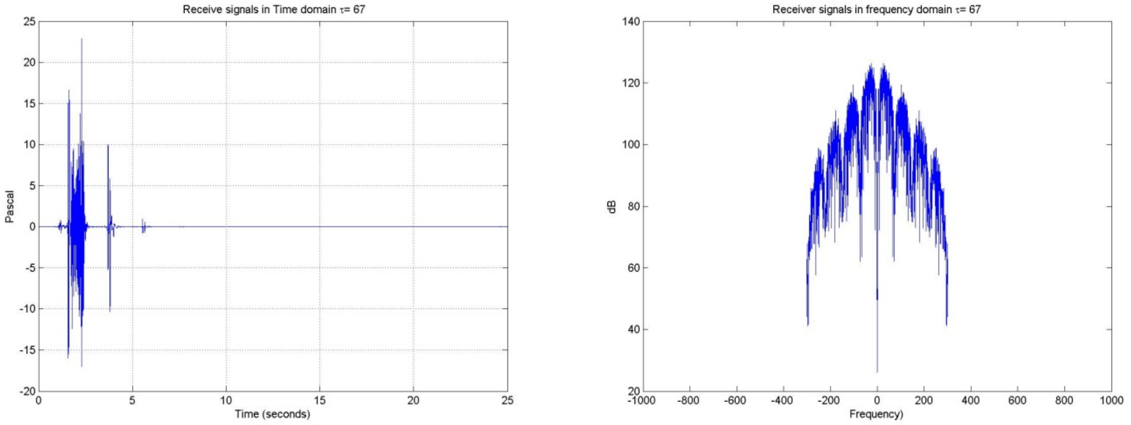


1000 km

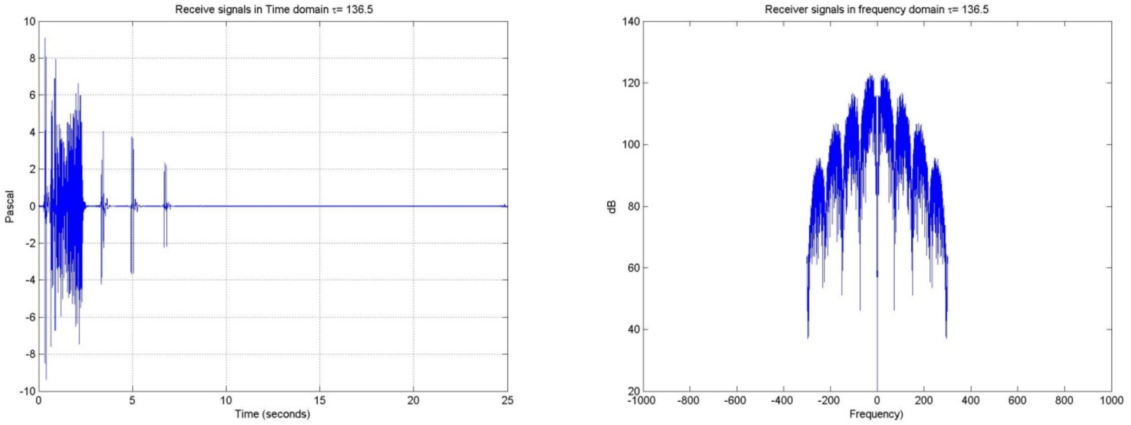


2000 km

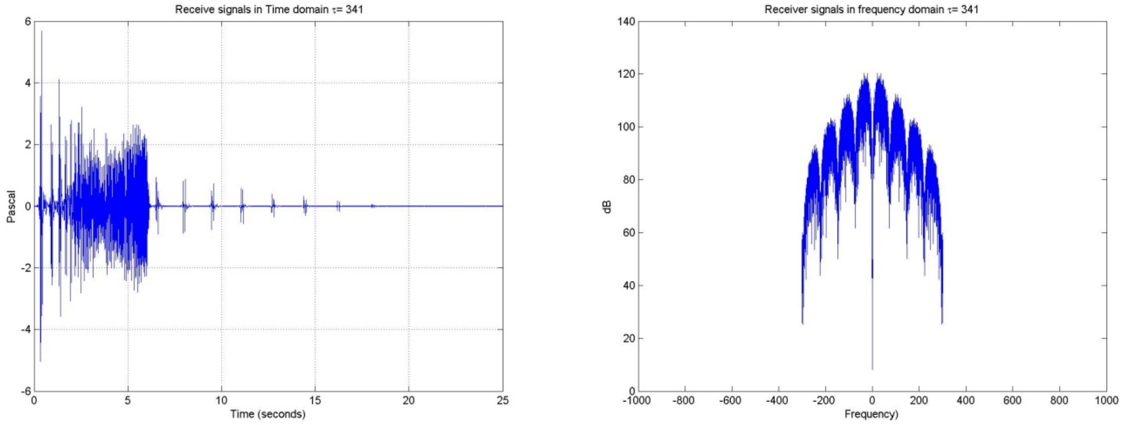
Receiver depth 200 m



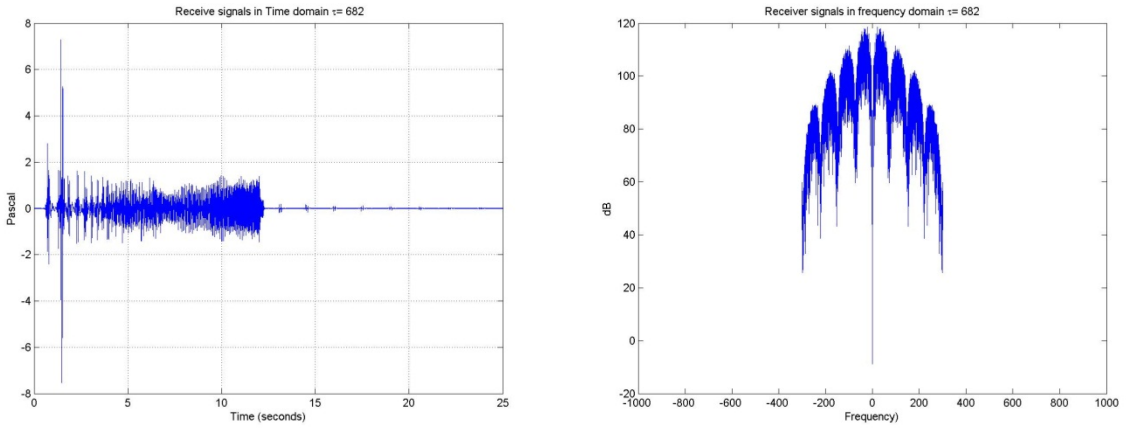
100 km



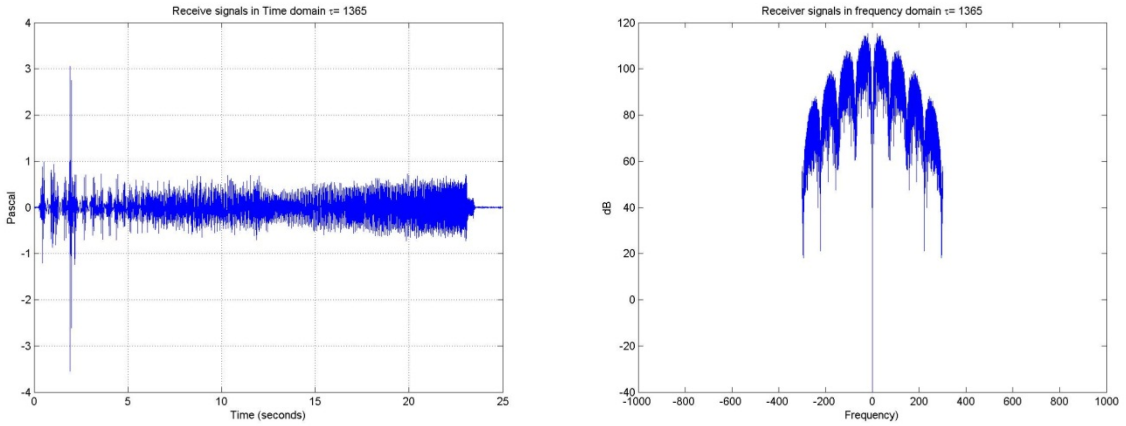
200 km



500 km



1000 km

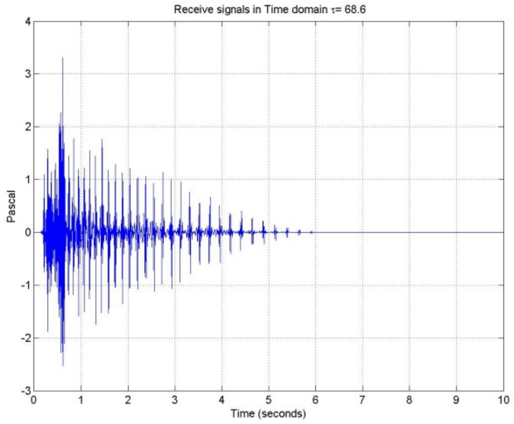


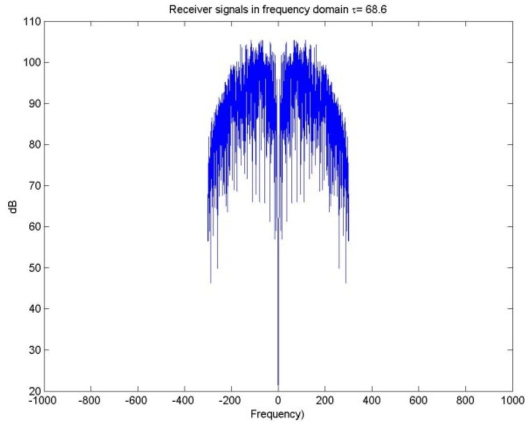
2000 km

11.5.2 Depth 500 m

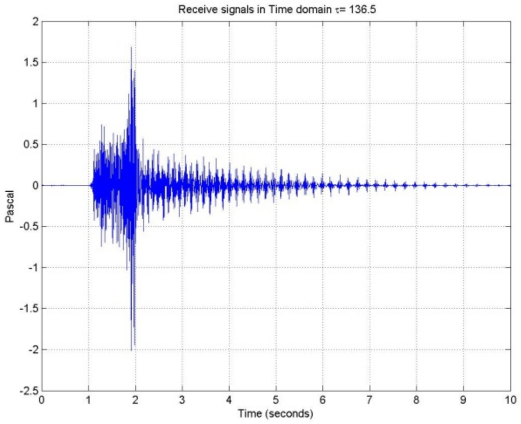
11.5.2.1 Station 715

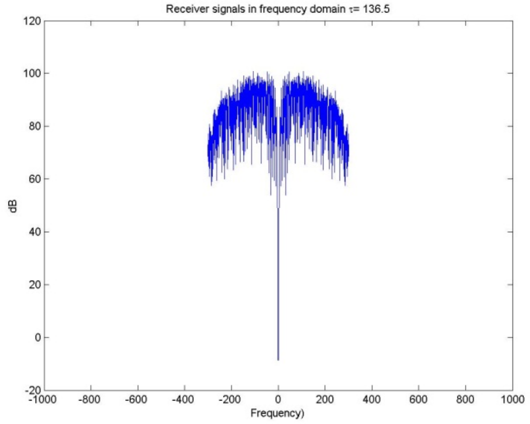
Receiver depth 10 m



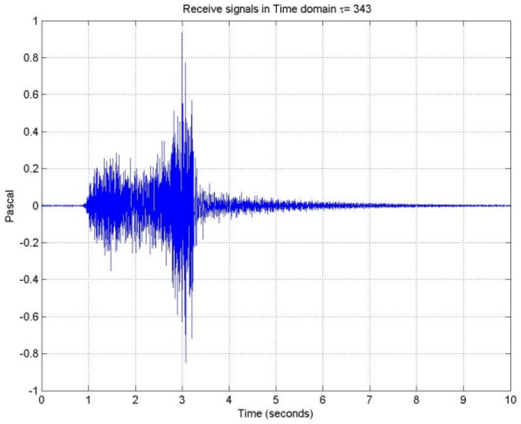


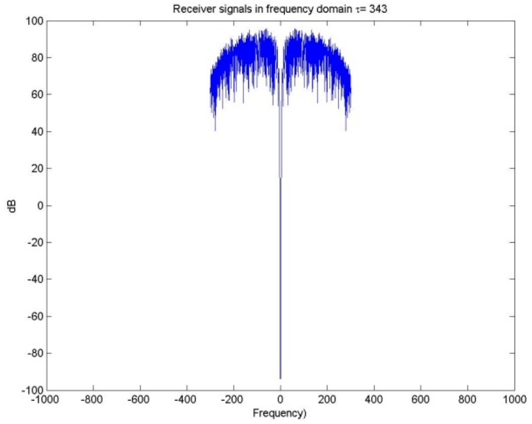
100 km



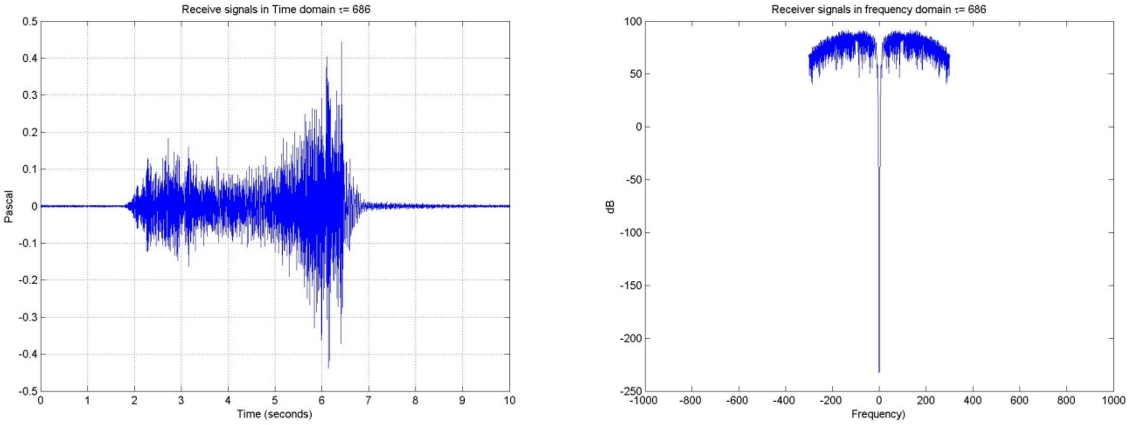


200 km

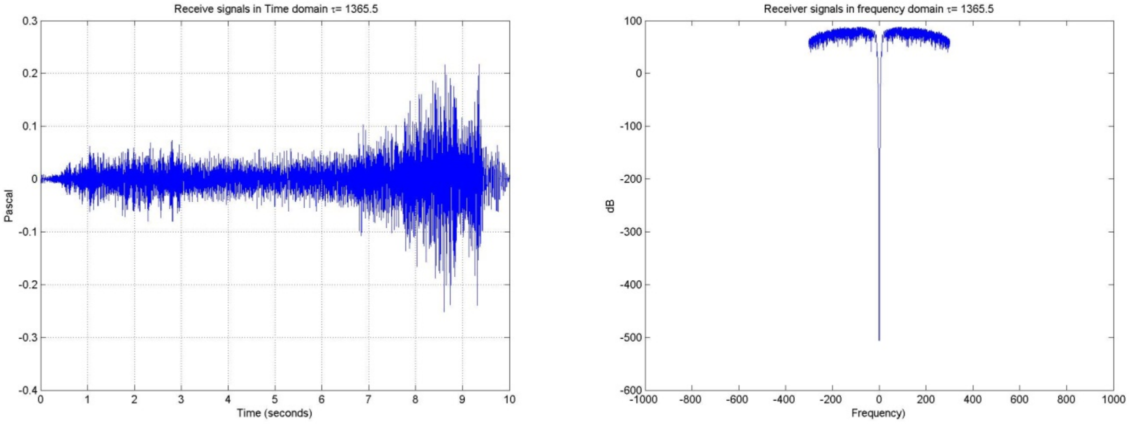




500 km

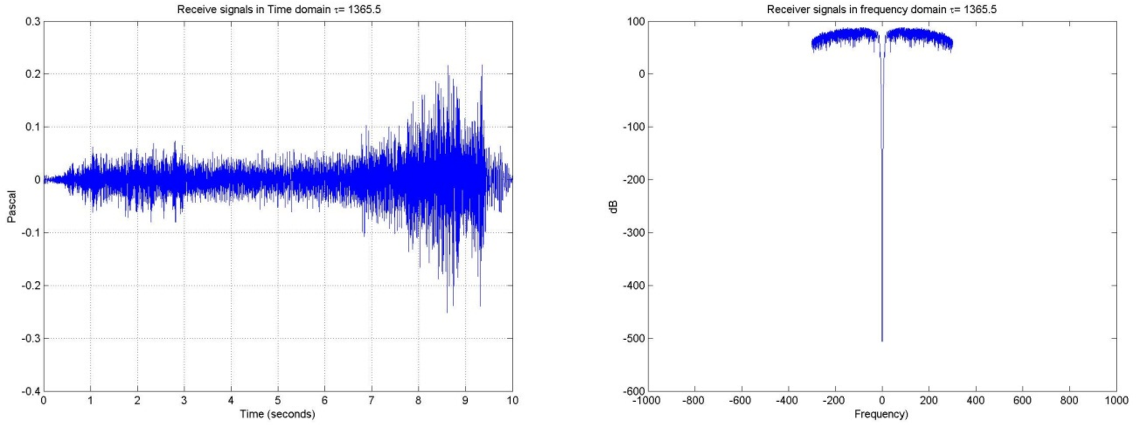


1000 km

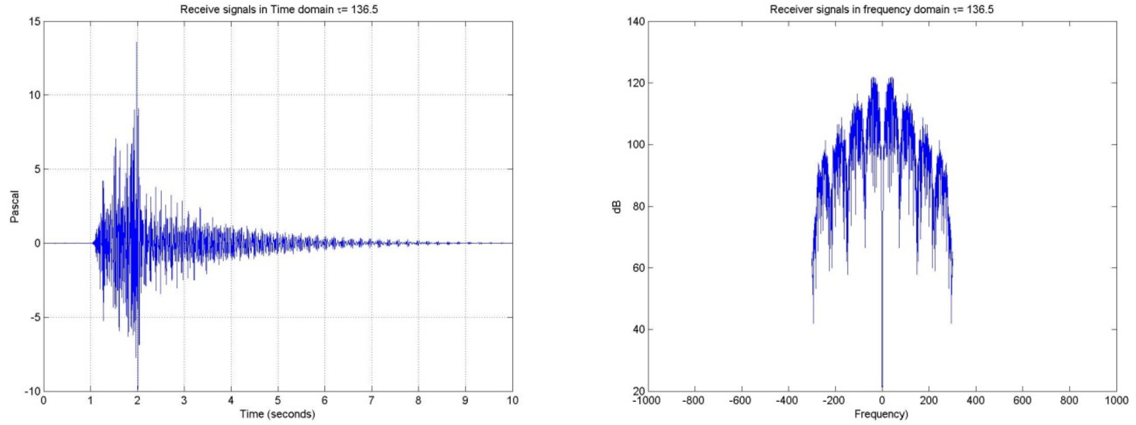


2000 km

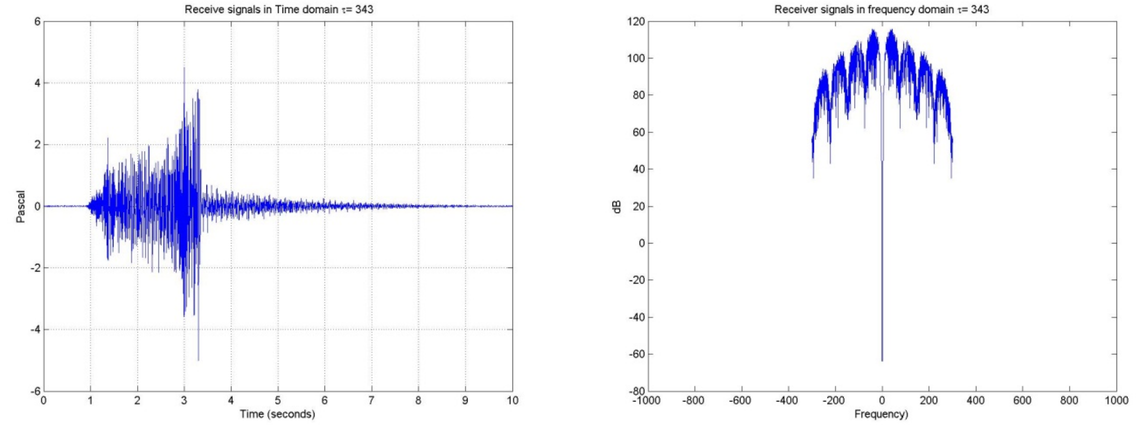
Receiver depth 50 m



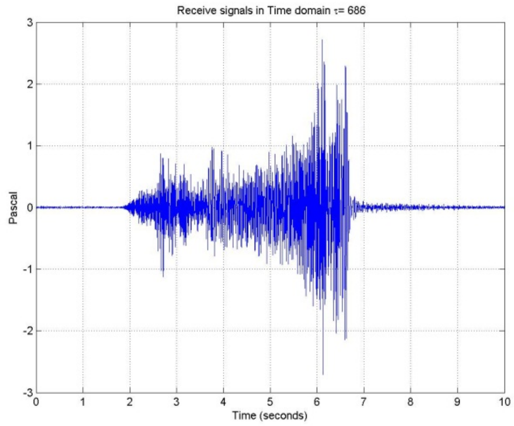
100 km

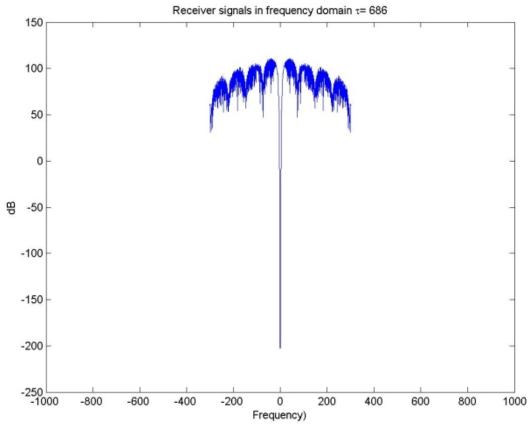


200 km

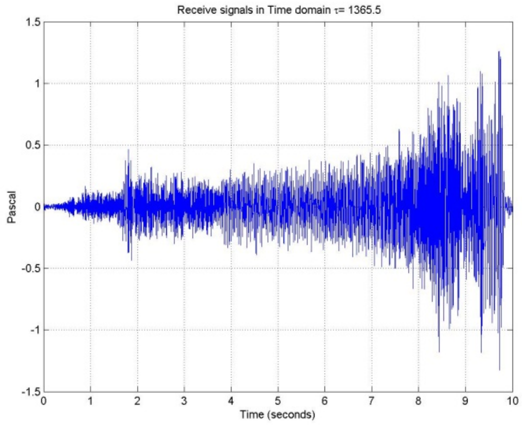


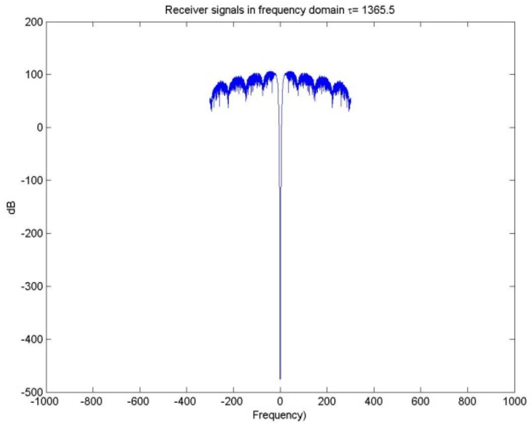
500 km





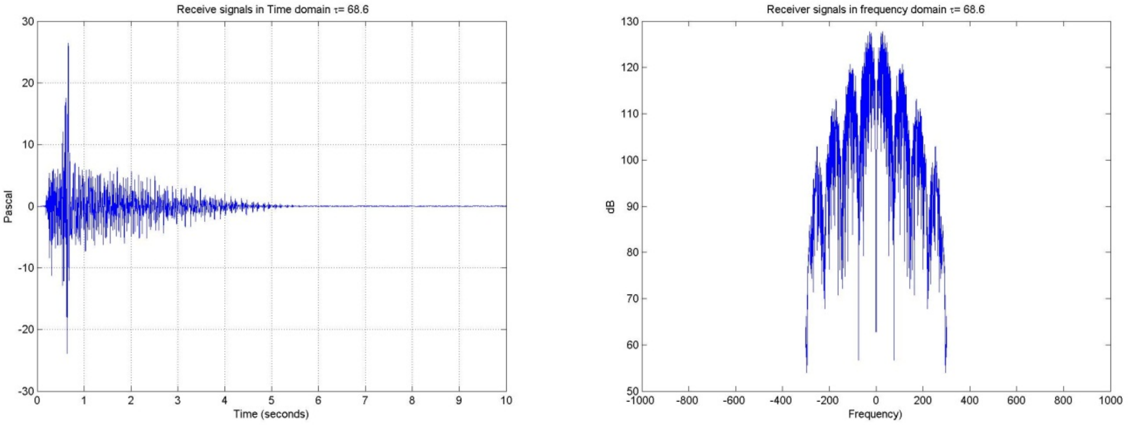
1000 km



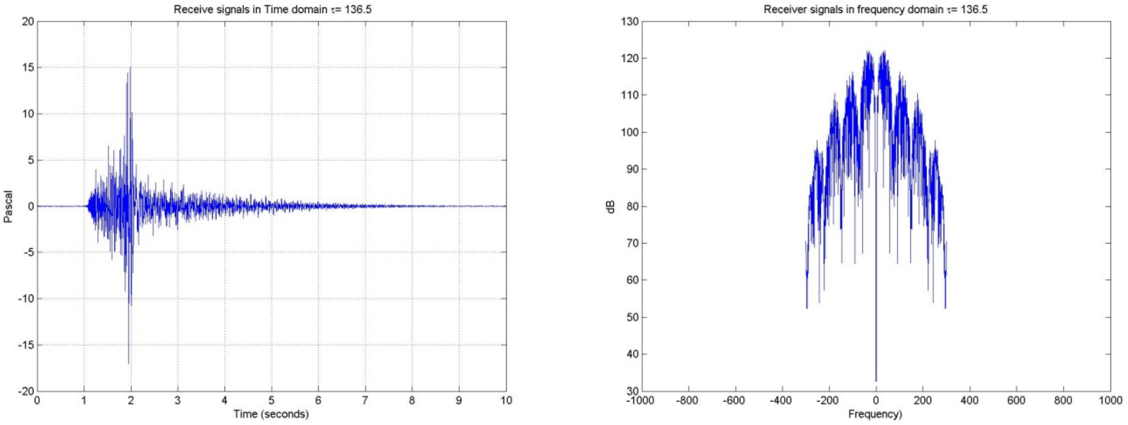


2000 km

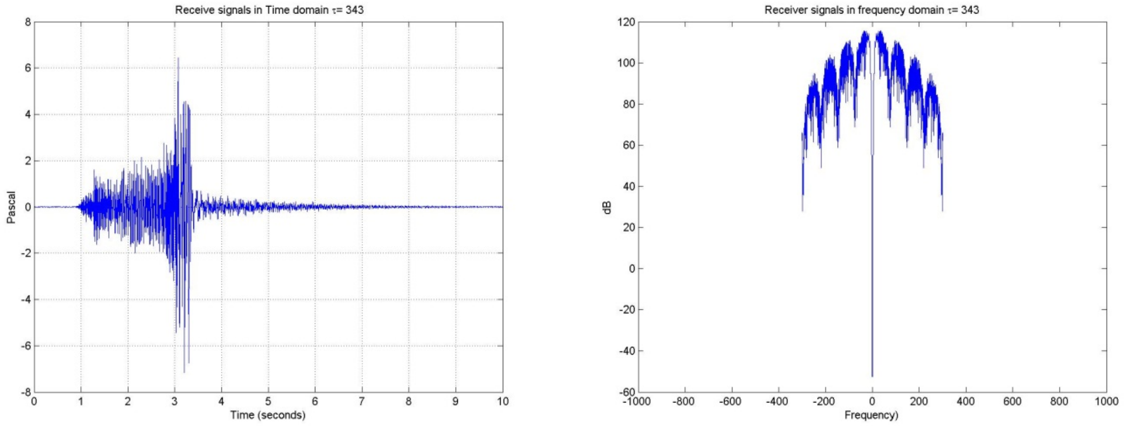
Receiver depth 200 m



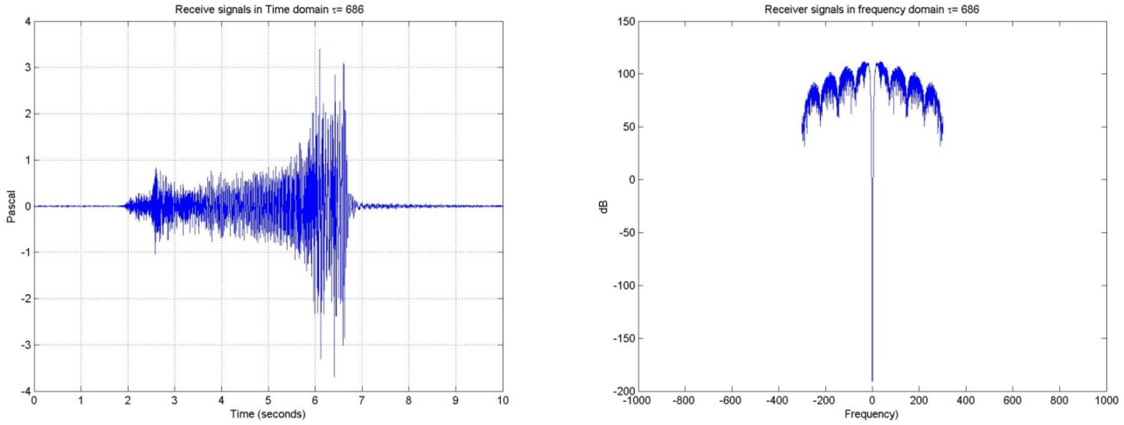
100 km



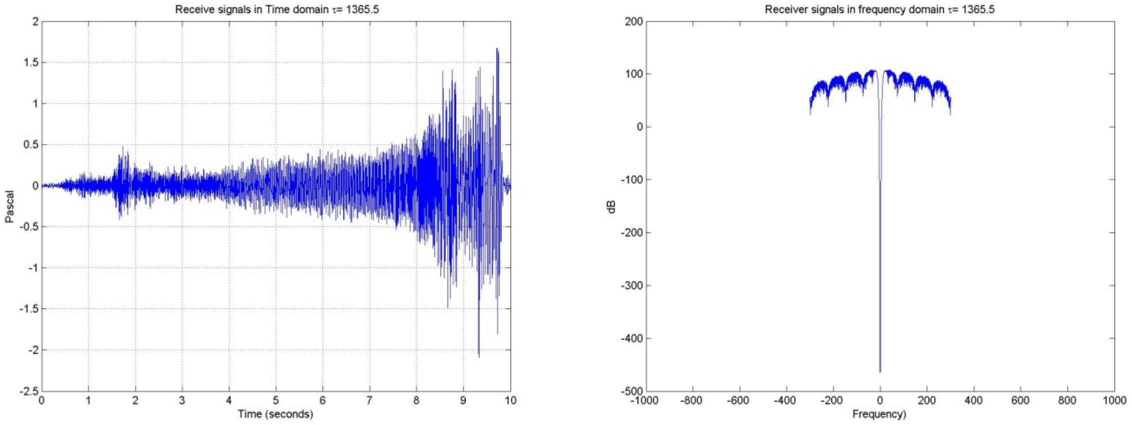
200 km



500 km



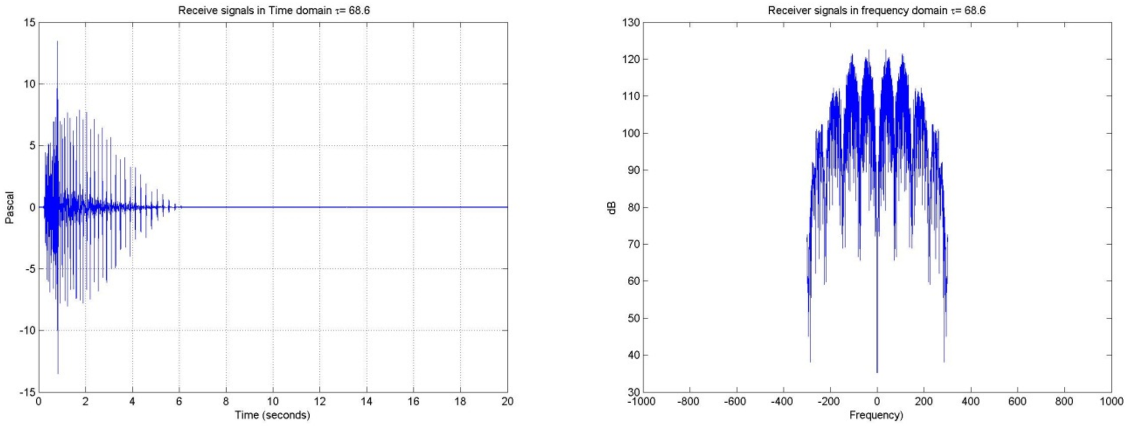
1000 km



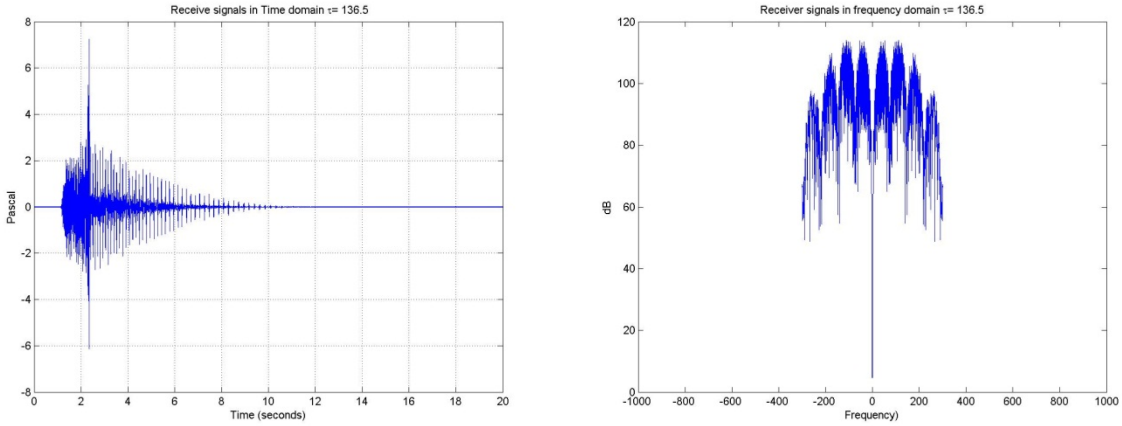
2000 km

11.5.2.2 Station 25

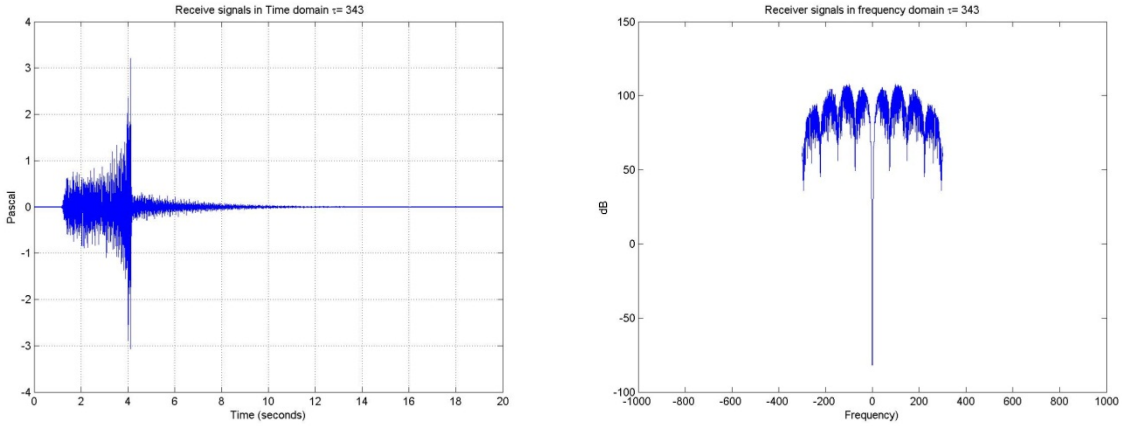
Receiver depth 10 m



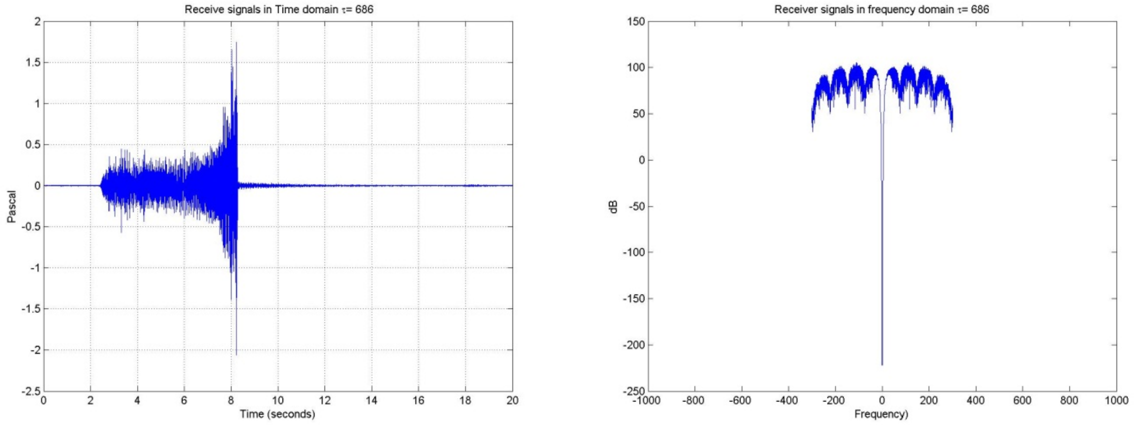
100 km



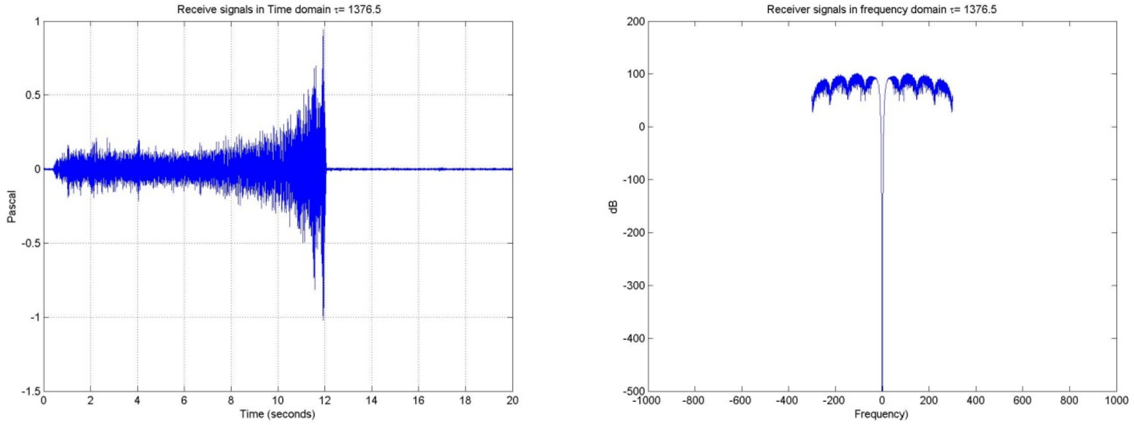
200 km



500 km

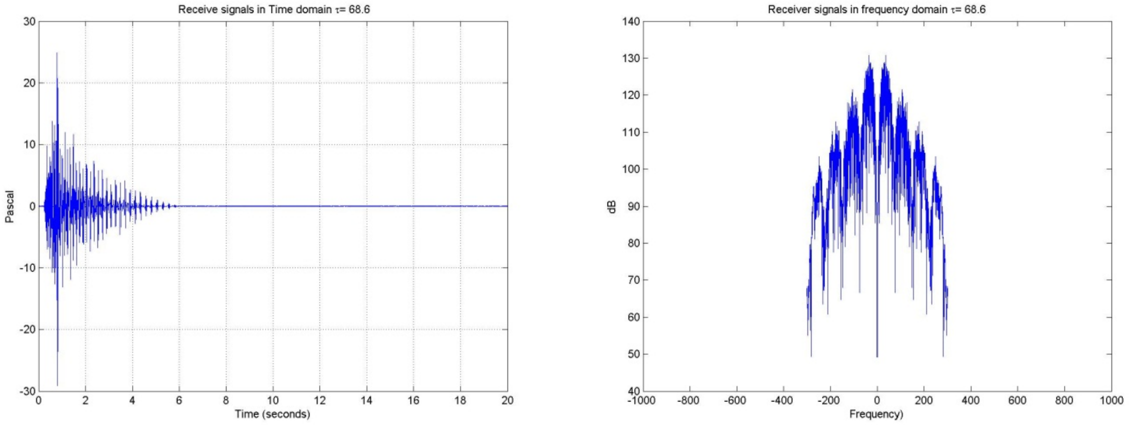


1000 km

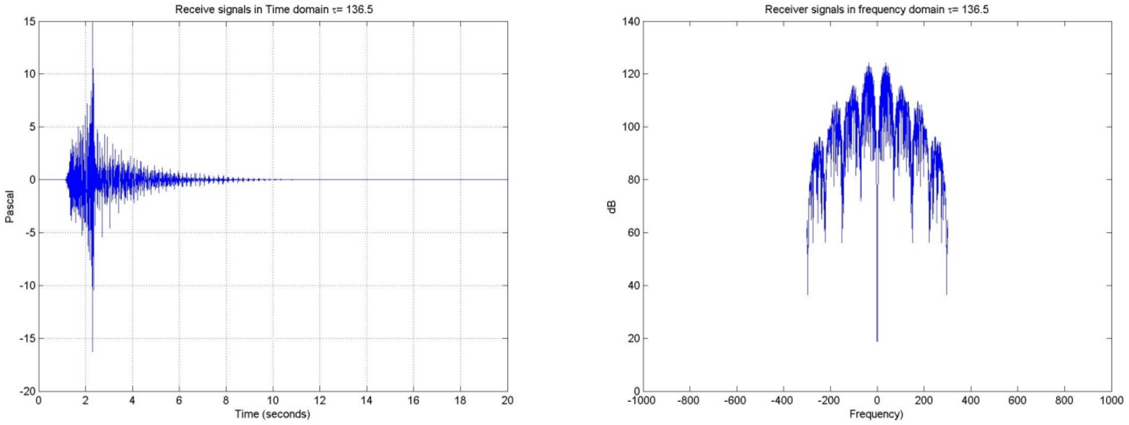


2000 km

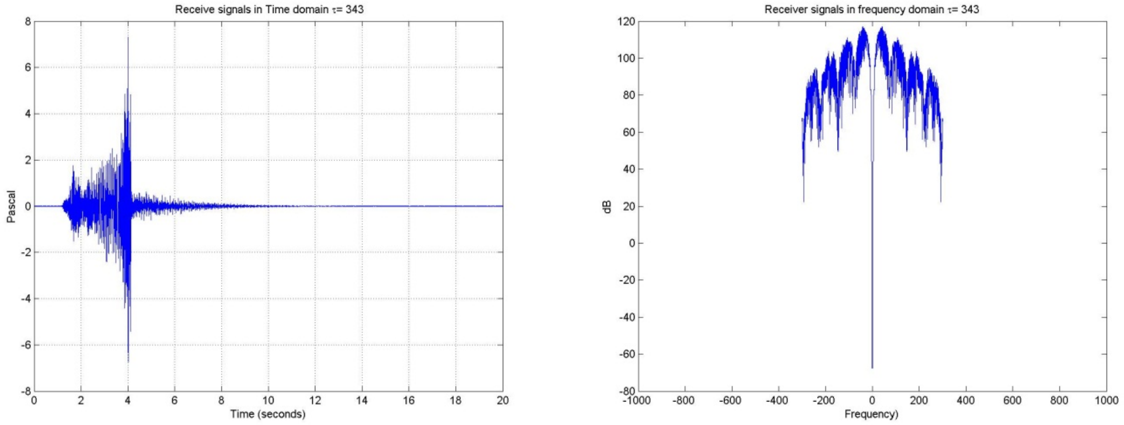
Receiver depth 50 m



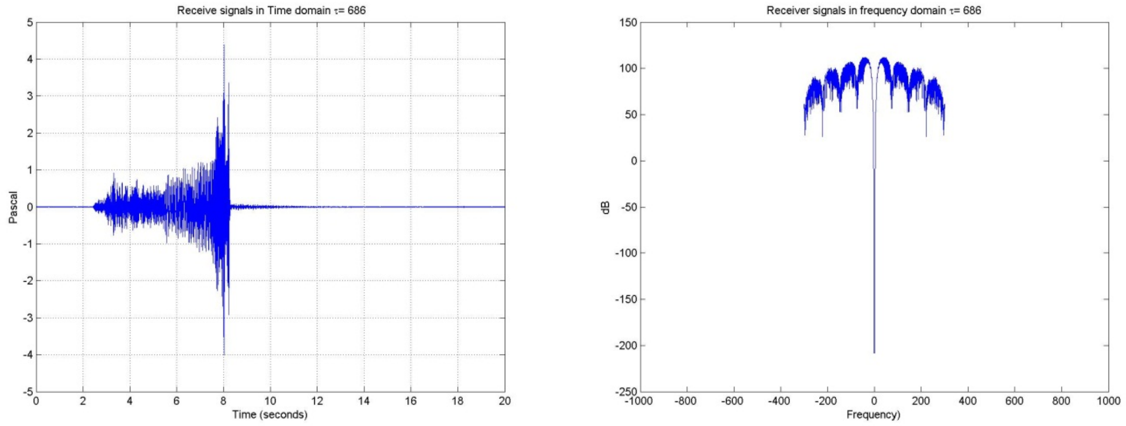
100 km



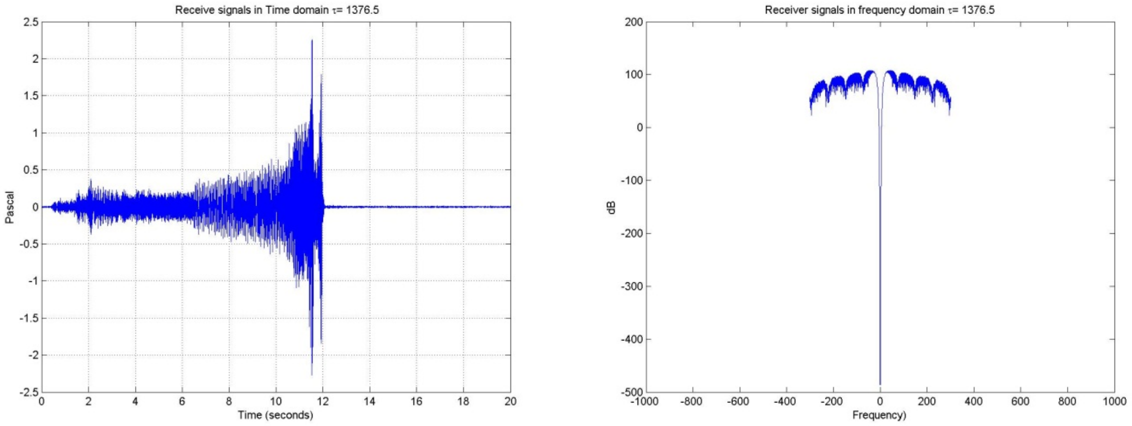
200 km



500 km

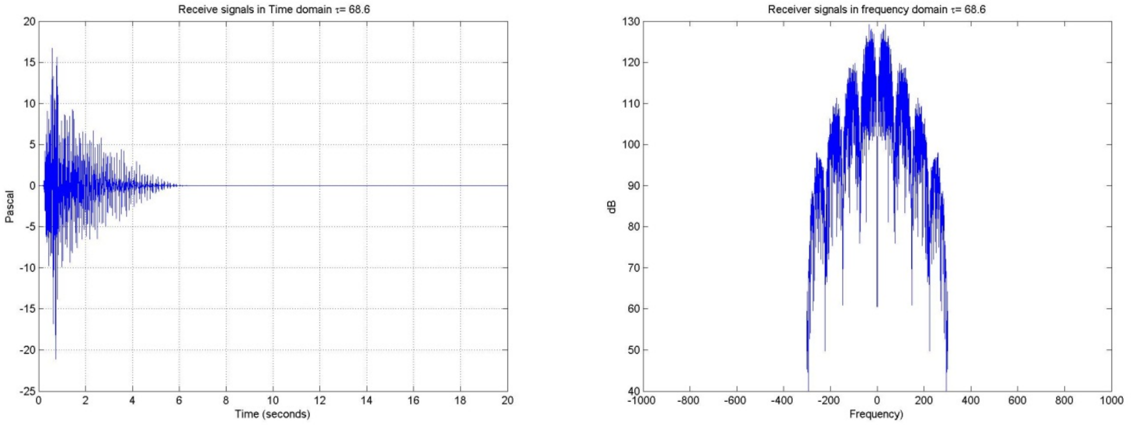


1000 km



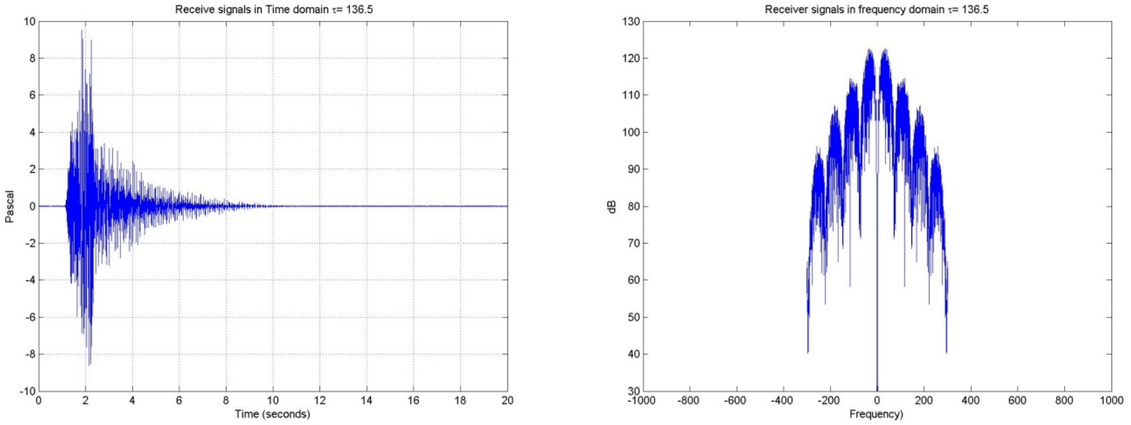
2000 km

Receiver depth 200 m


Receive signals in Time domain τ= 68.6

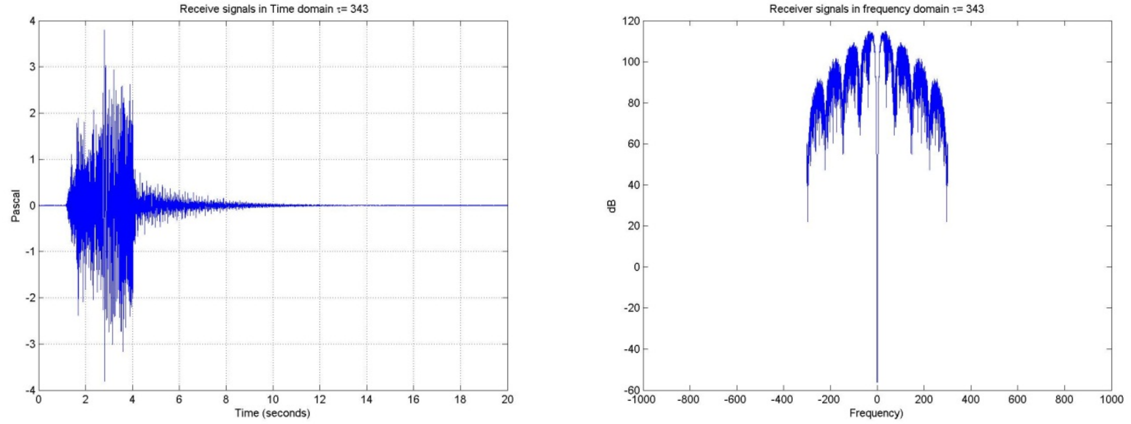
Receiver signals in frequency domain τ= 68.6

100 km


Receive signals in Time domain τ= 136.5

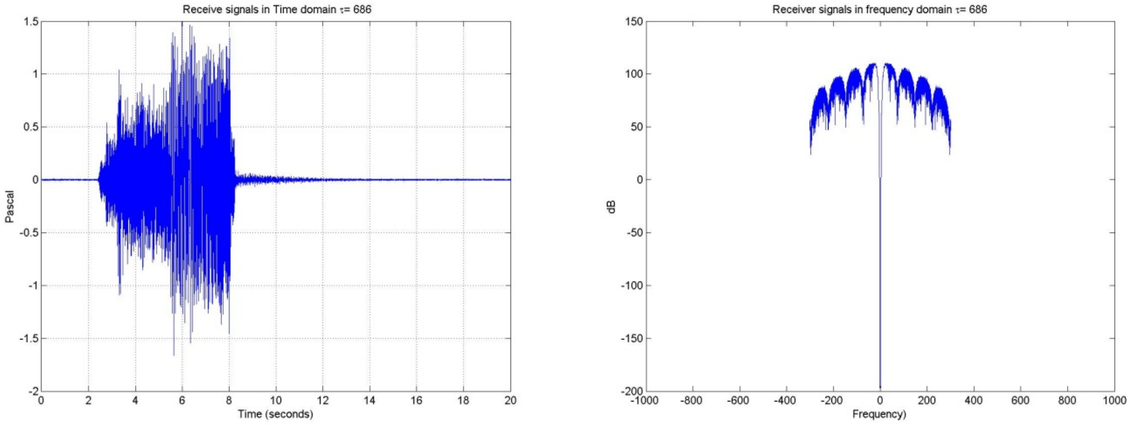
Receiver signals in frequency domain τ= 136.5

200 km

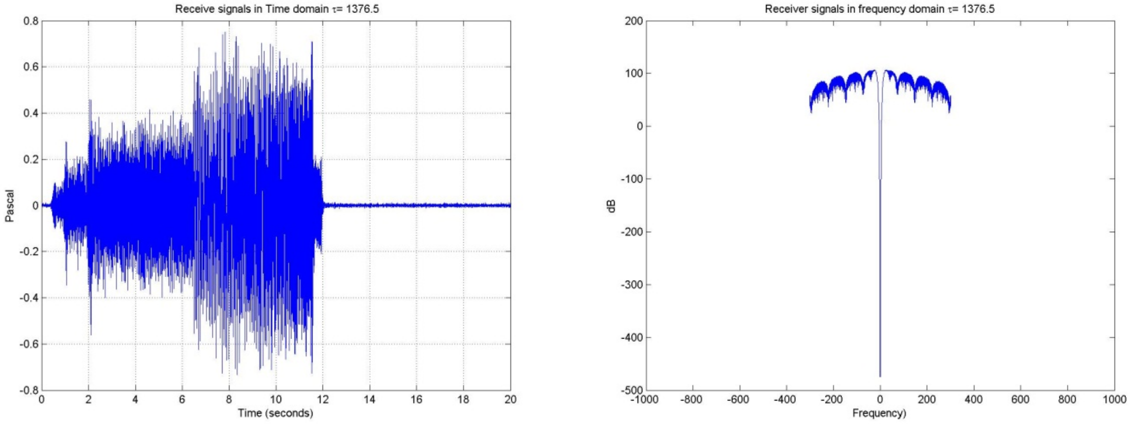

Receive signals in Time domain τ= 343

Receiver signals in frequency domain τ= 343

500 km



1000 km



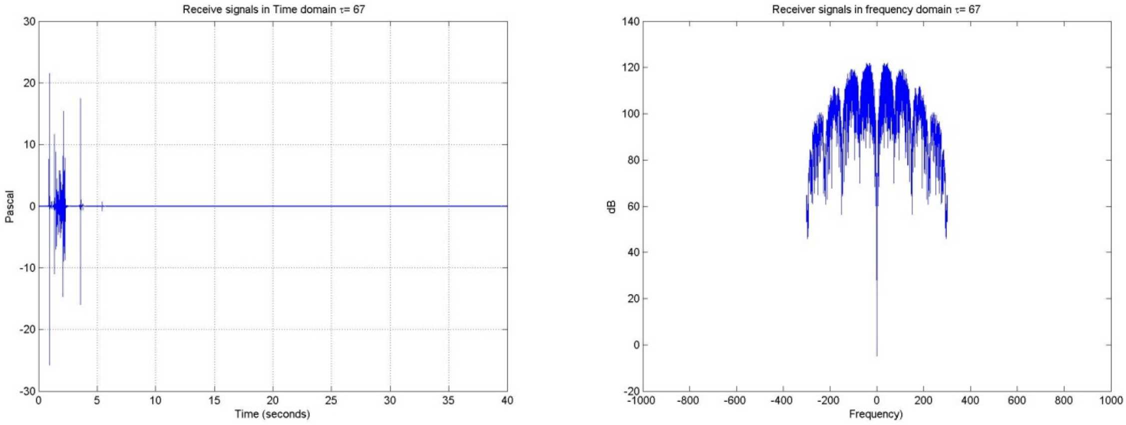
2000 km

11.6 8 G-gun+Bolt Array, source depth 10 m

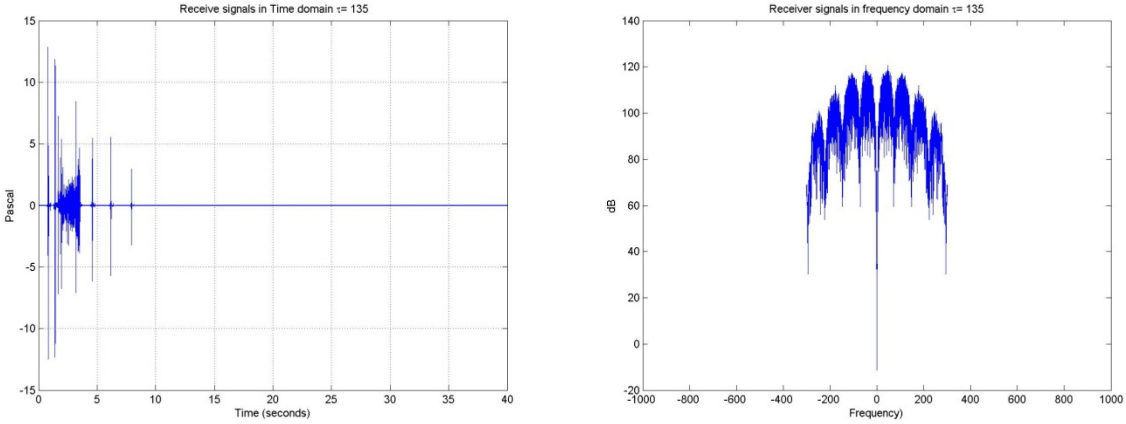
11.6.1 Depth 4000 m

11.6.1.1 Station 715

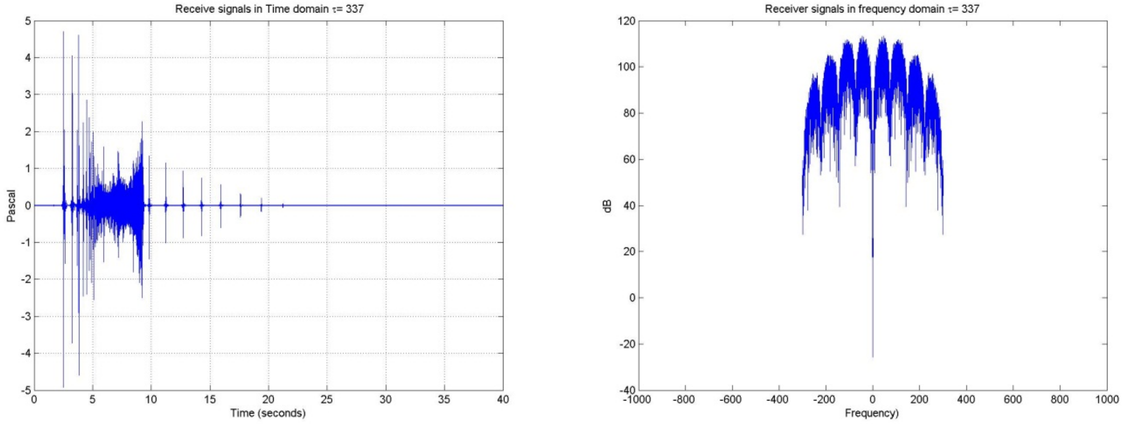
Receiver depth 10 m



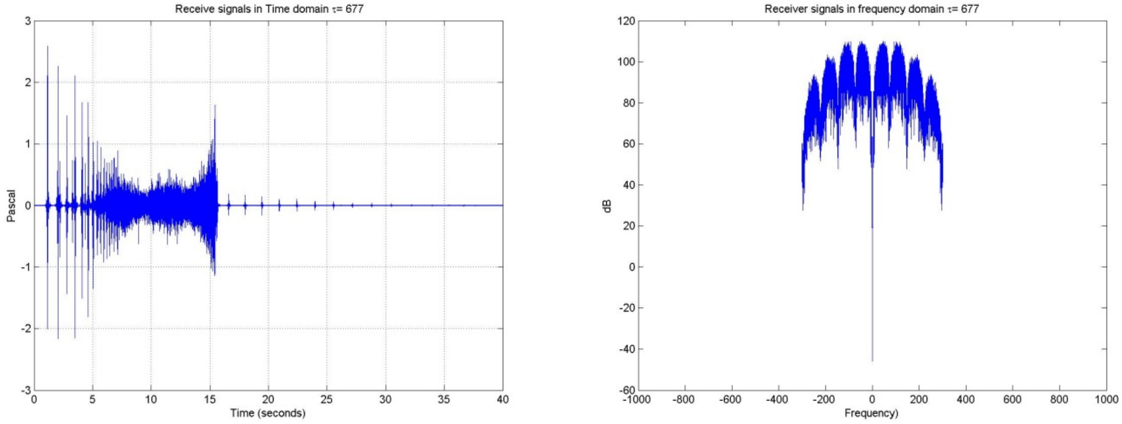
100 km



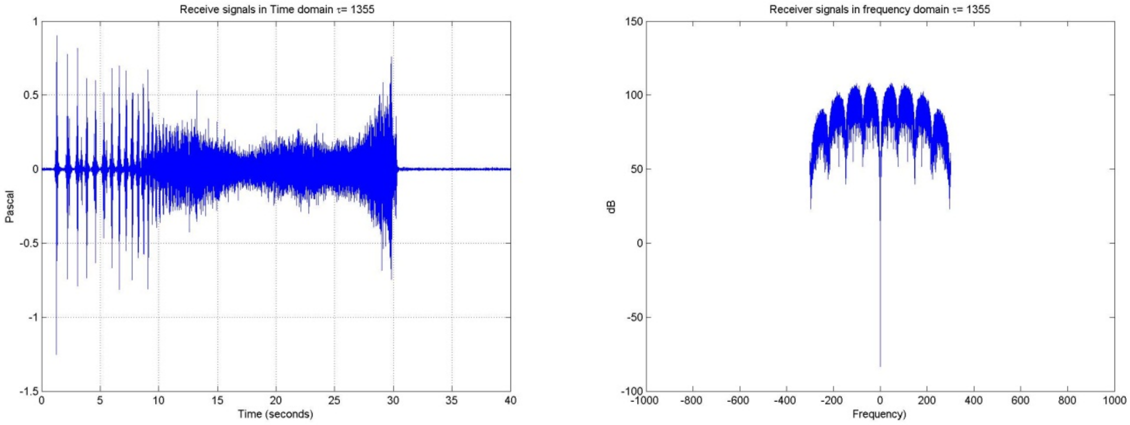
200 km



500 km

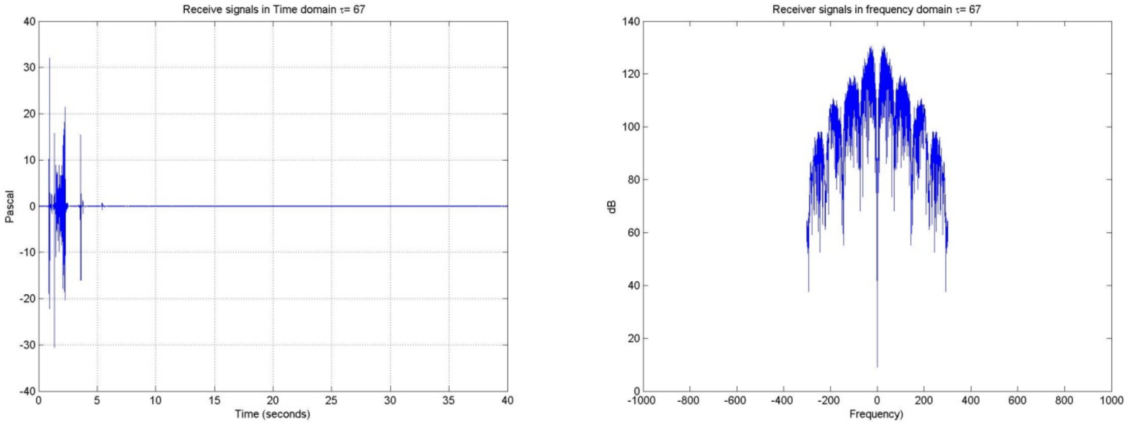


1000 km

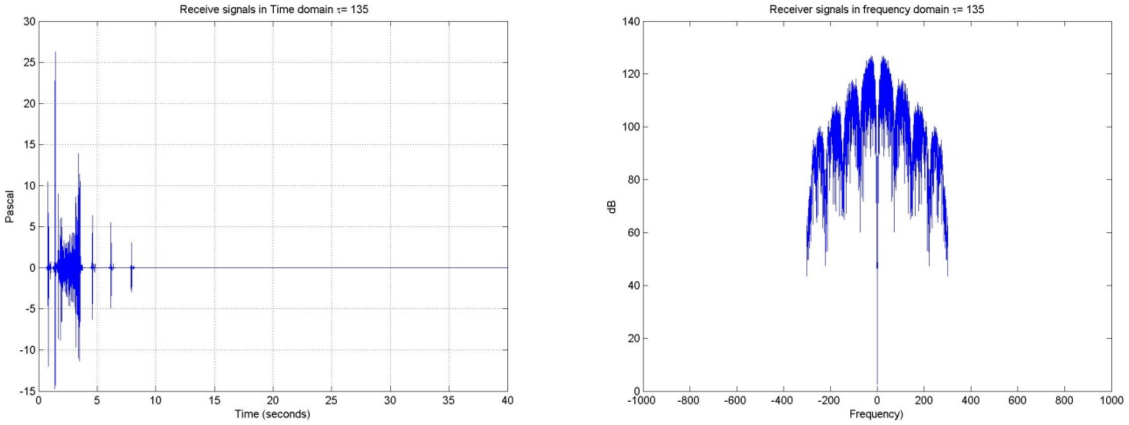


2000 km

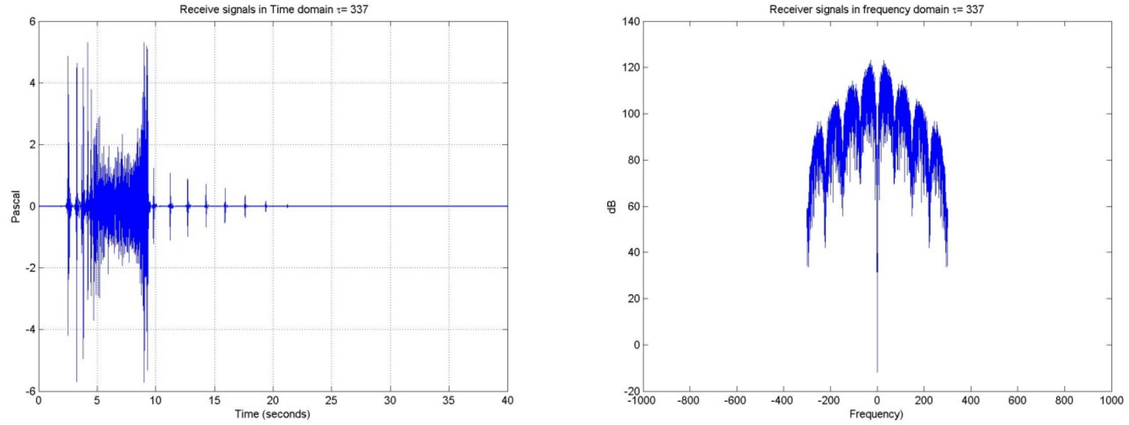
Receiver depth 50 m



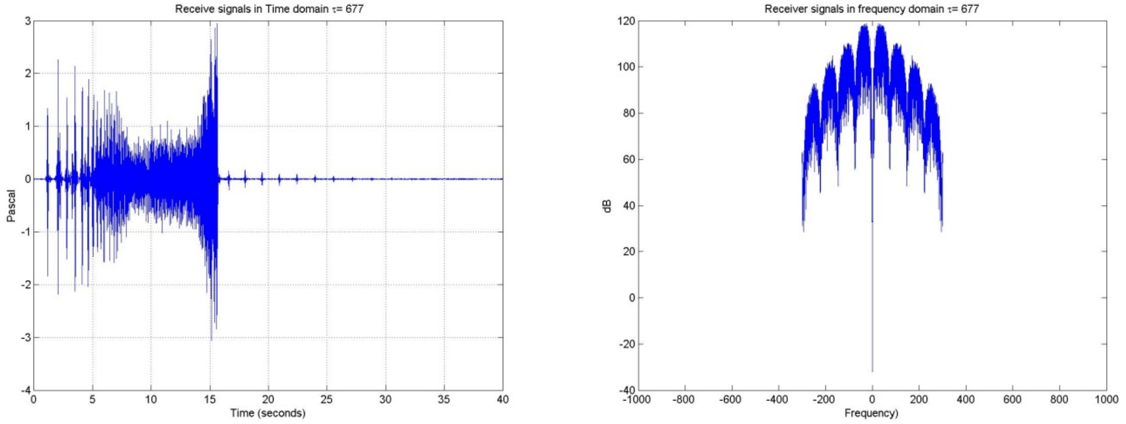
100 km



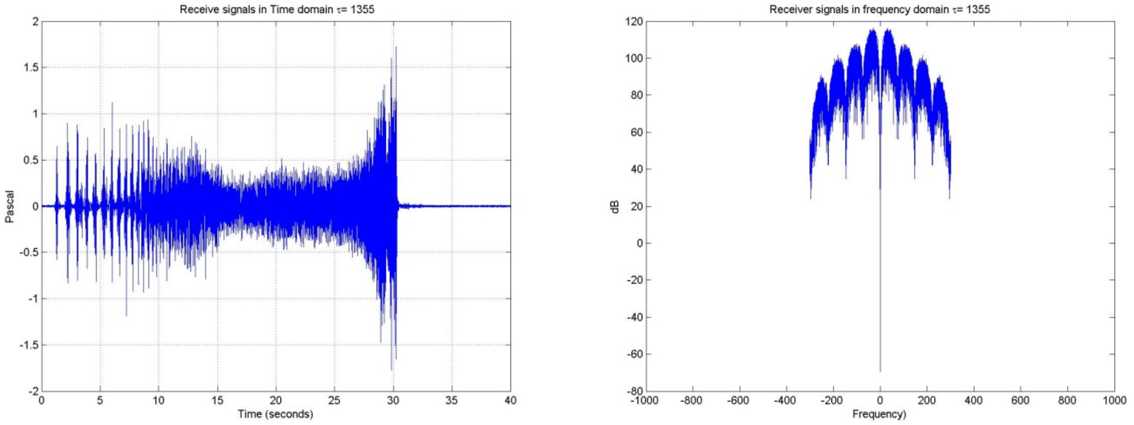
200 km



500 km

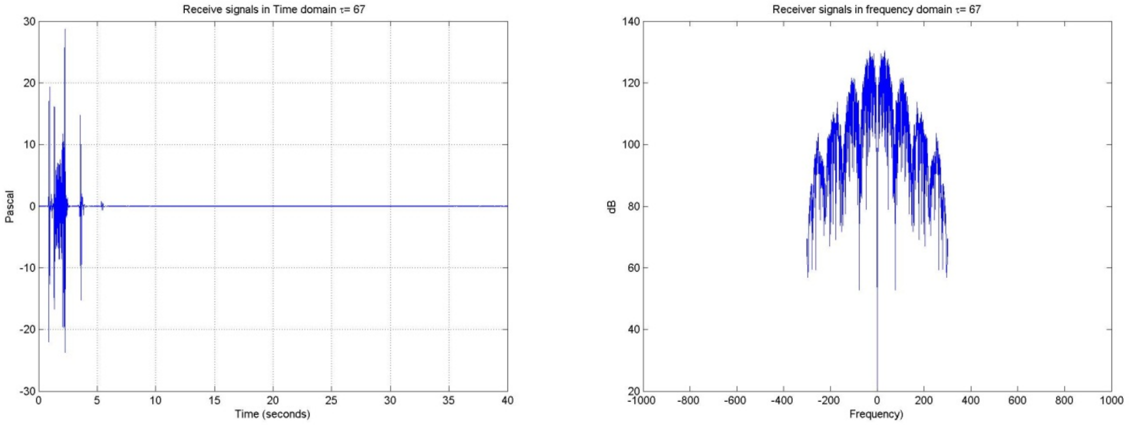


1000 km

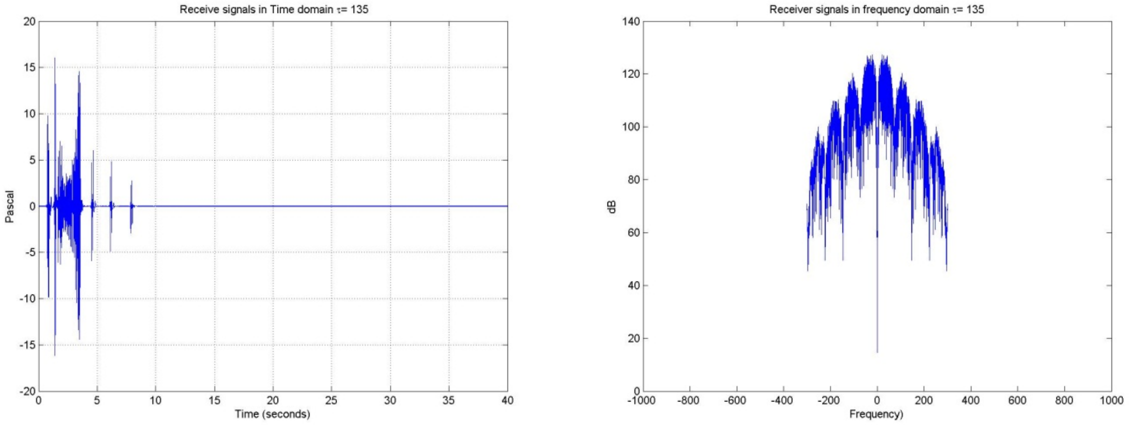


2000 km

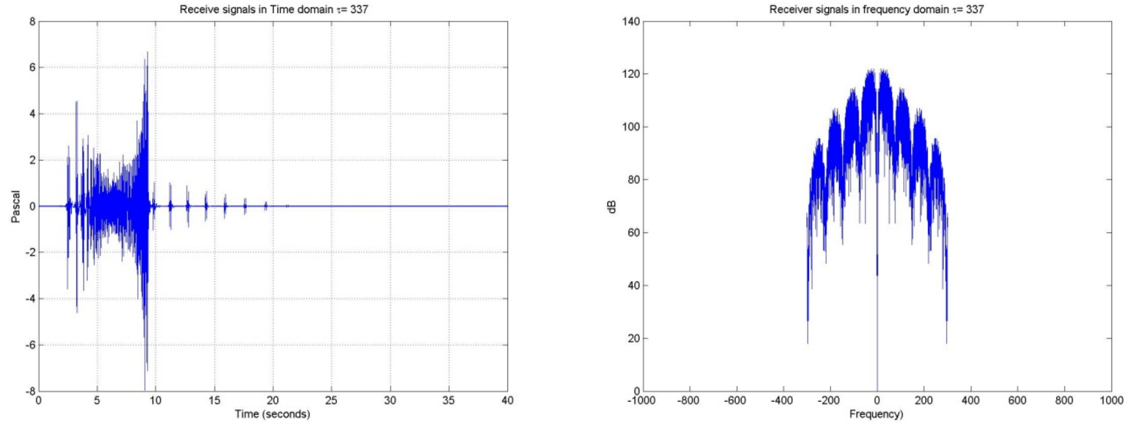
Receiver depth 200 m



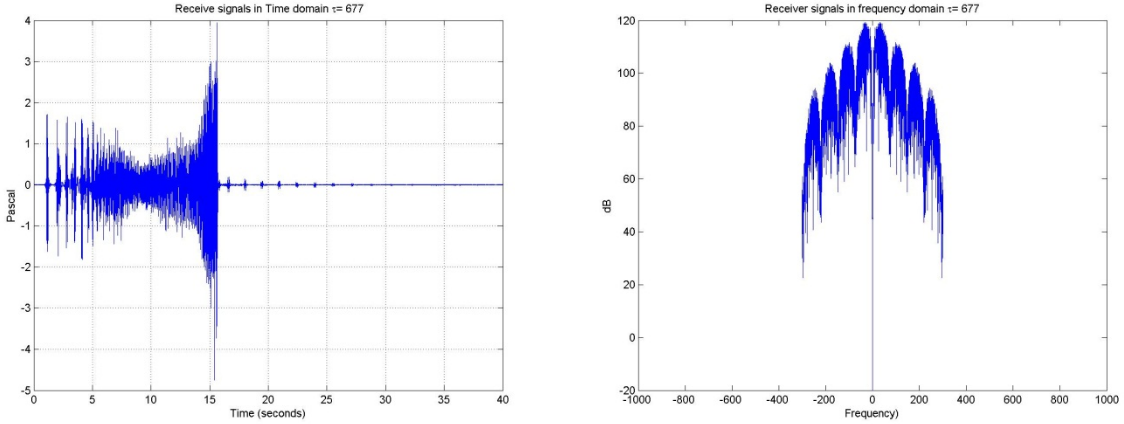
100 km



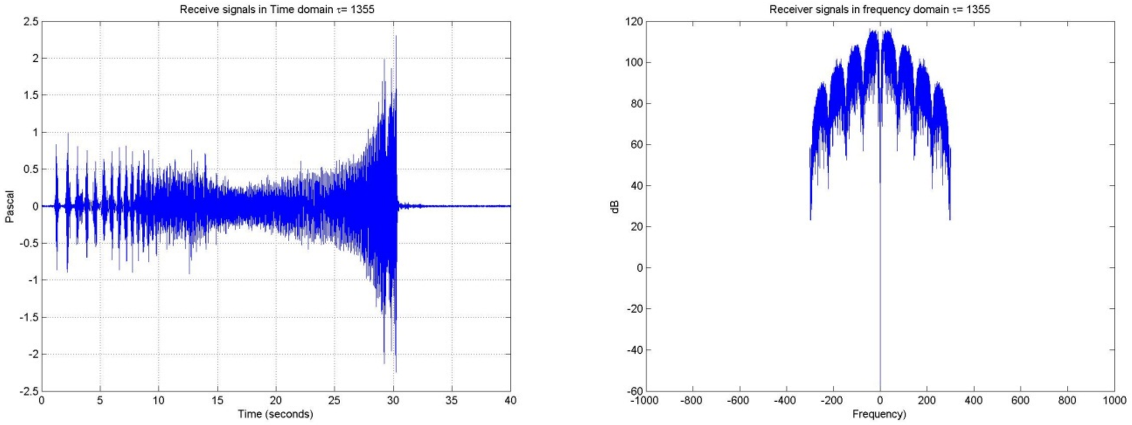
200 km



500 km



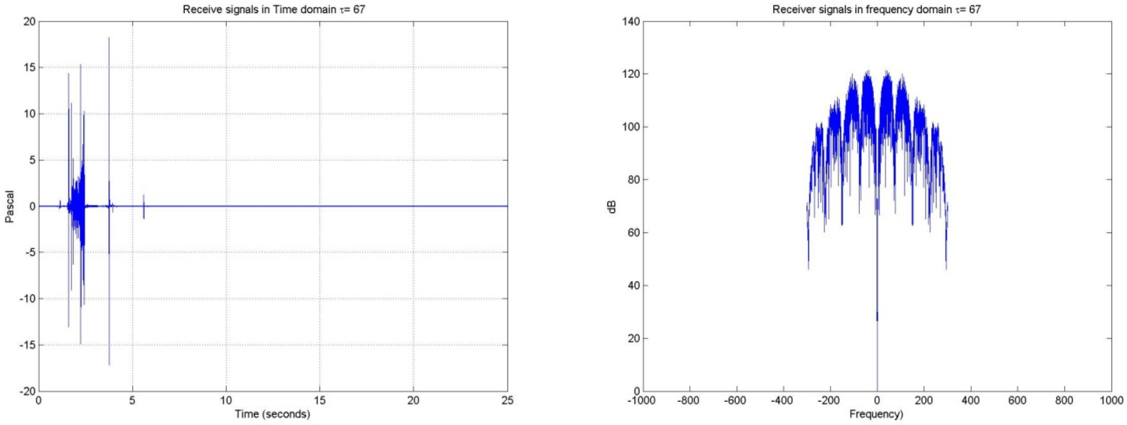
1000 km



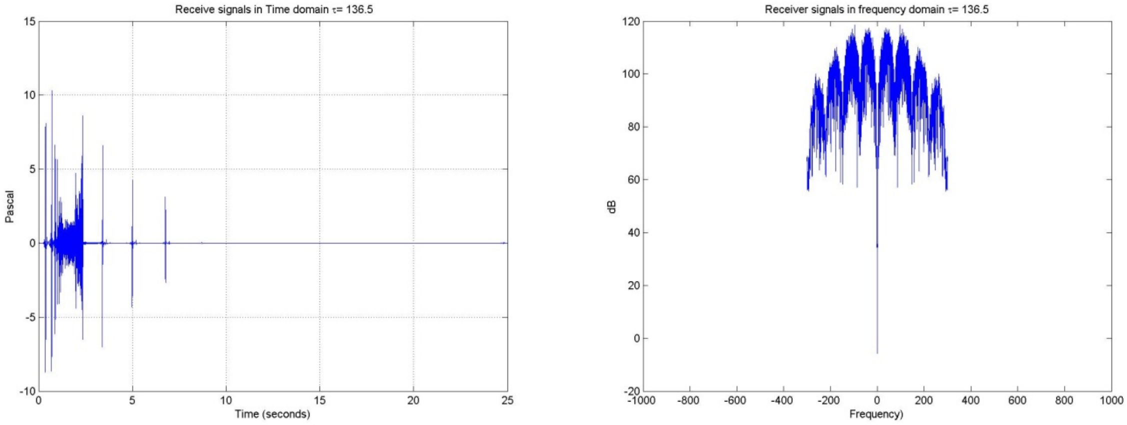
2000 km

11.6.1.2 Station 25

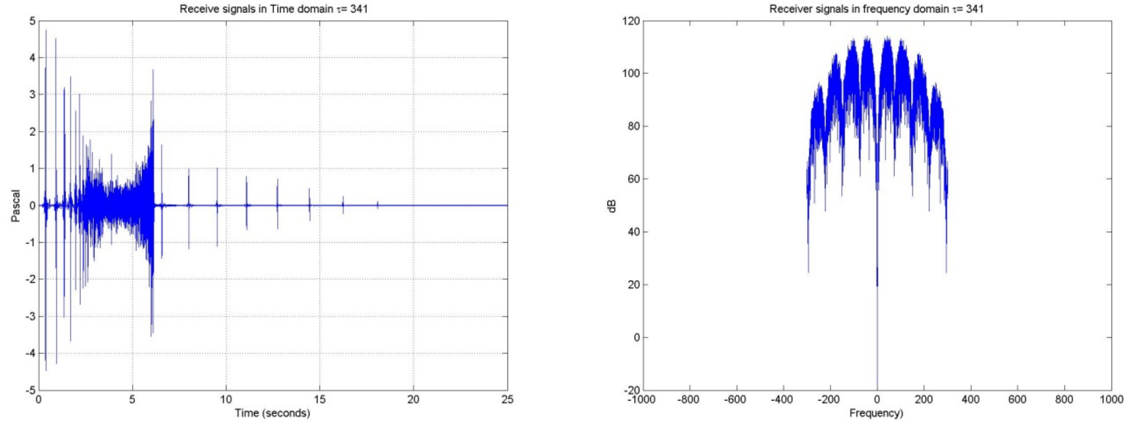
Receiver depth 10 m



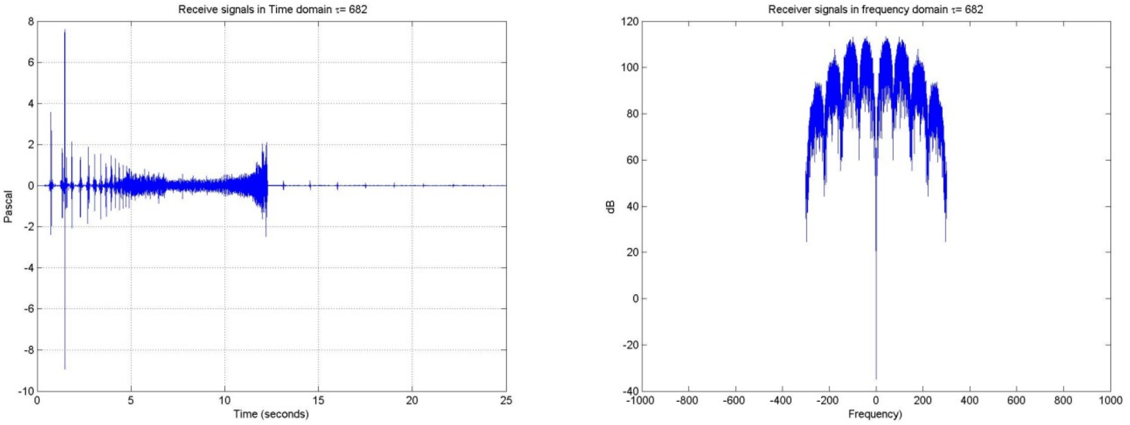
100 km



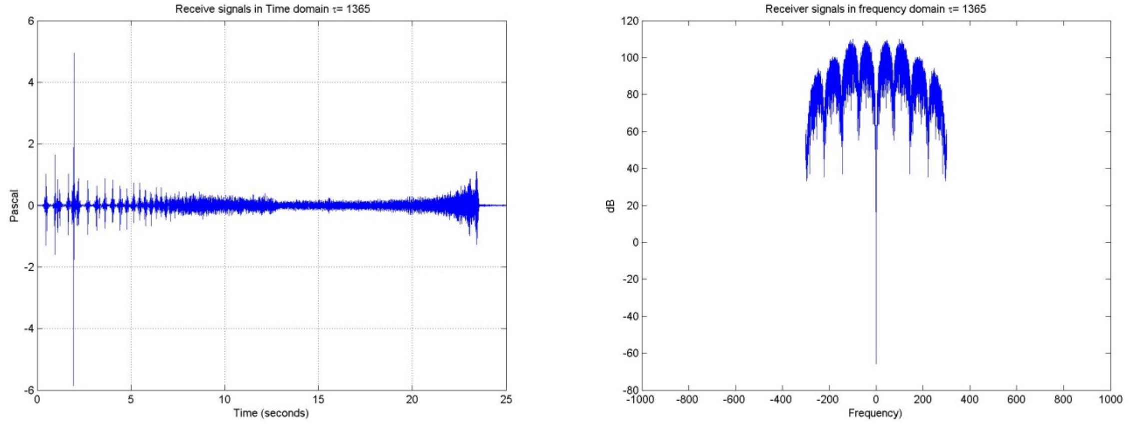
200 km



500 km

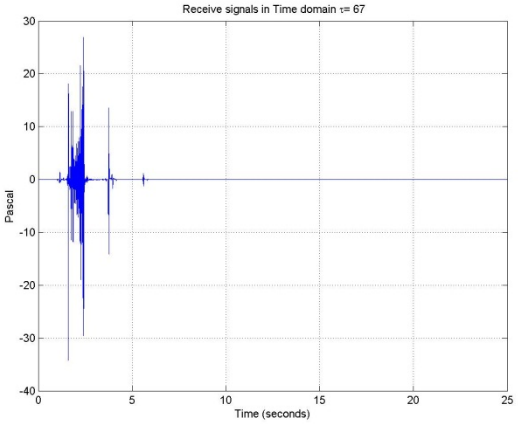


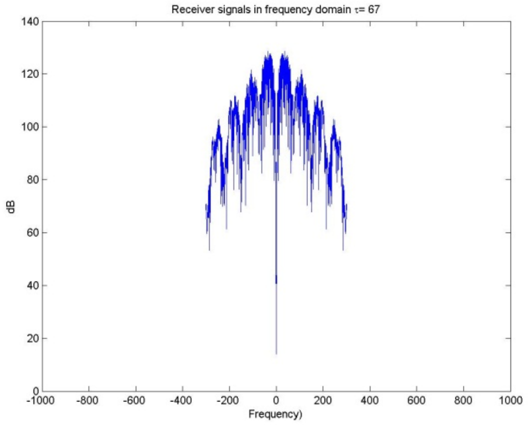
1000 km



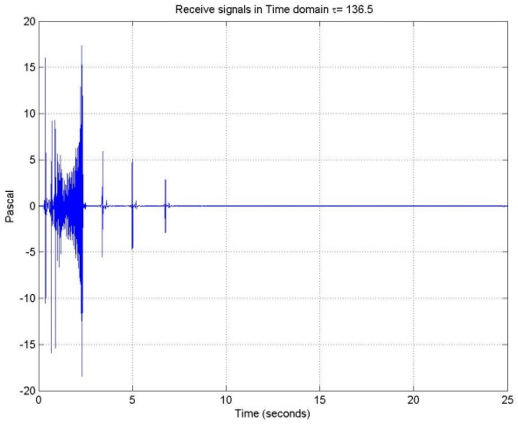
2000 km

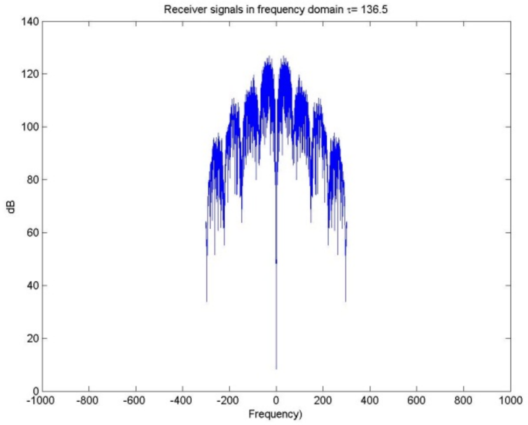
Receiver depth 50 m



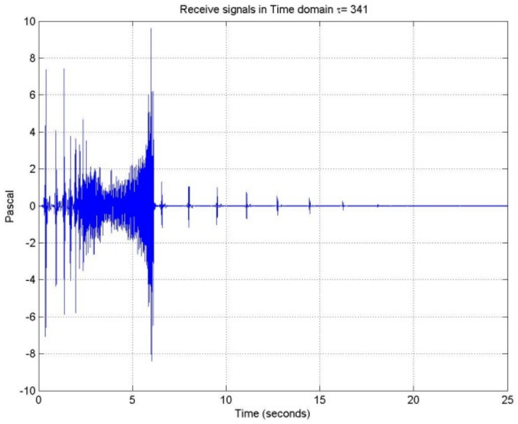


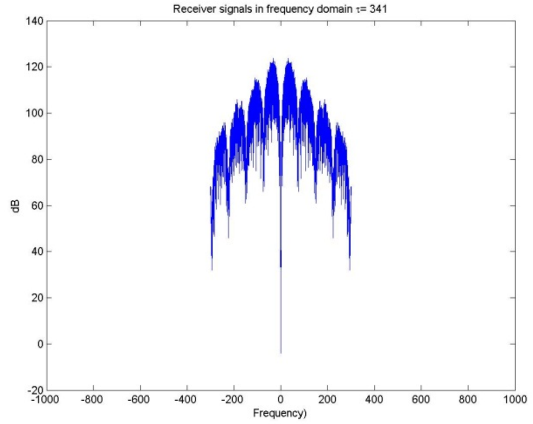
100 km



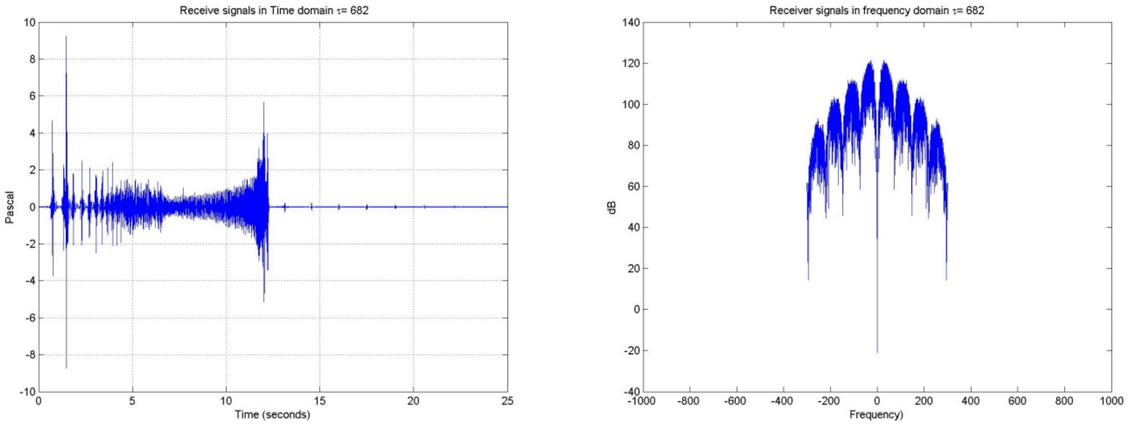


200 km

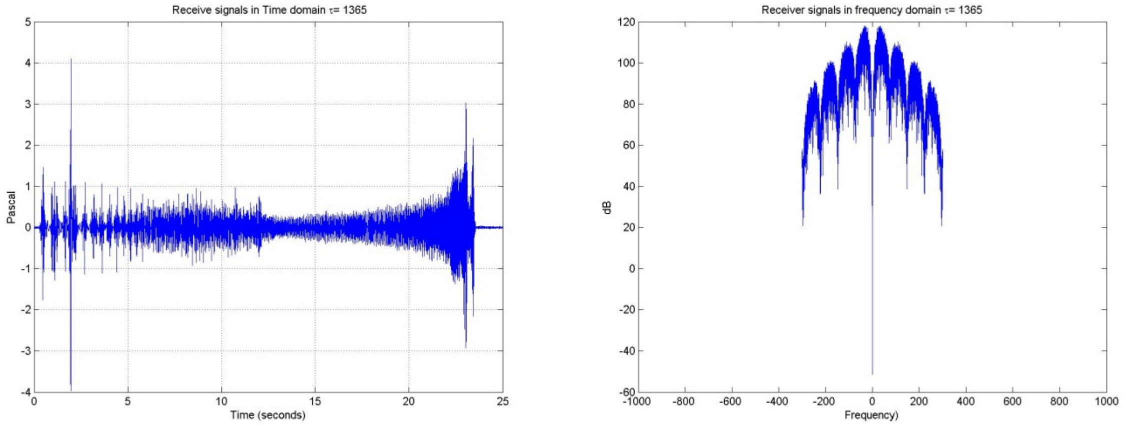




500 km

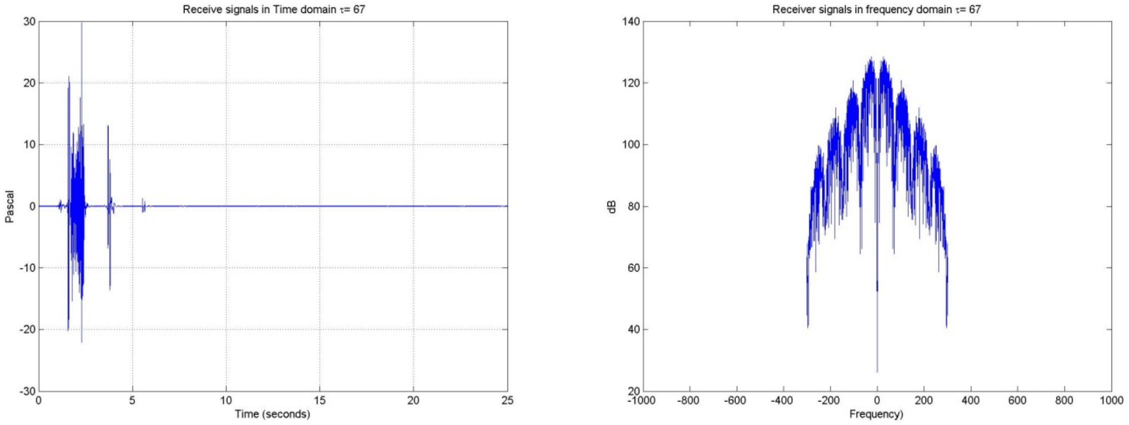


1000 km

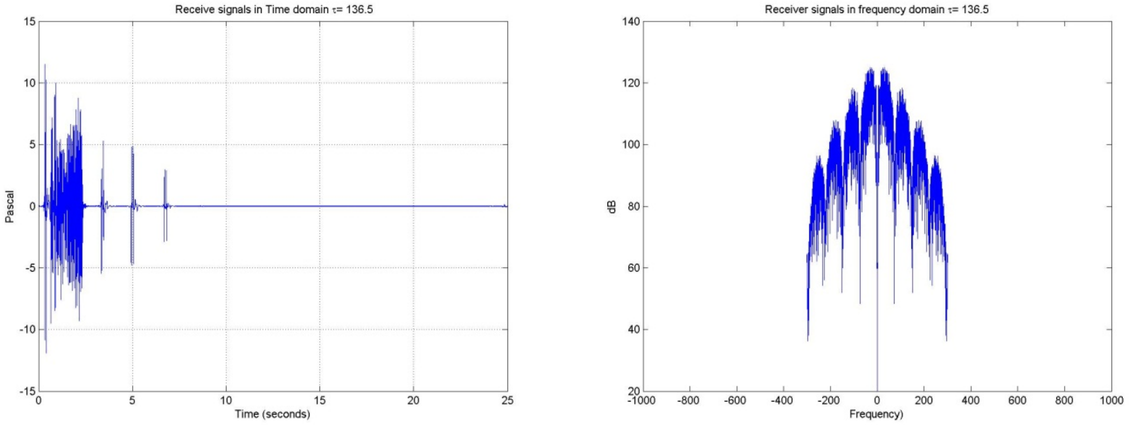


2000 km

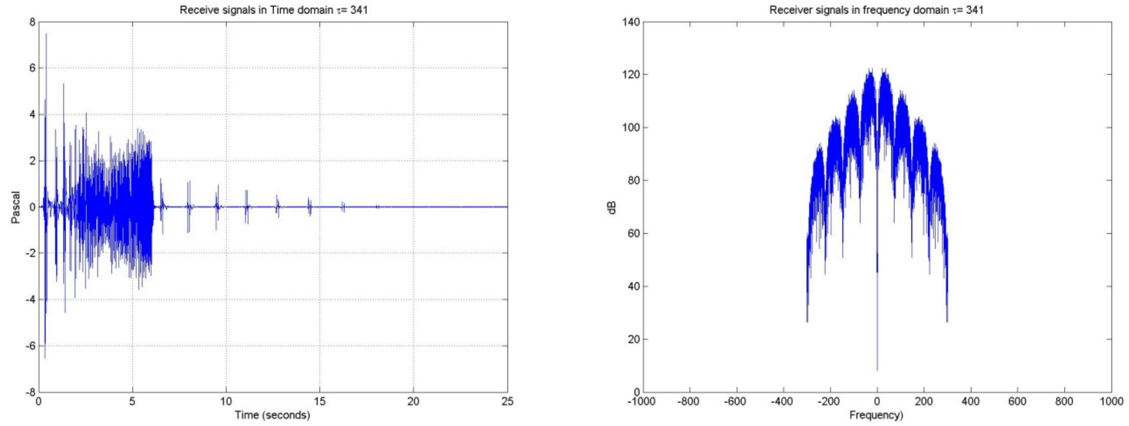
Receiver depth 200 m



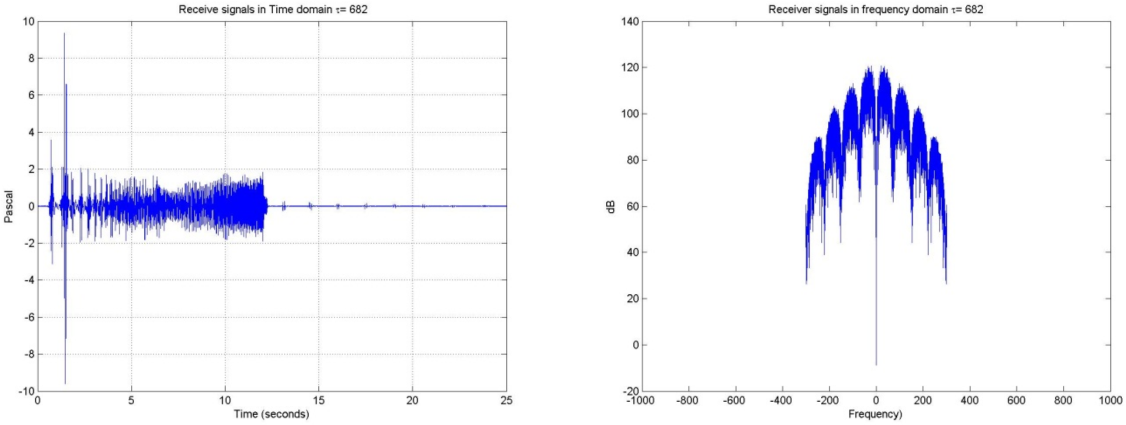
100 km



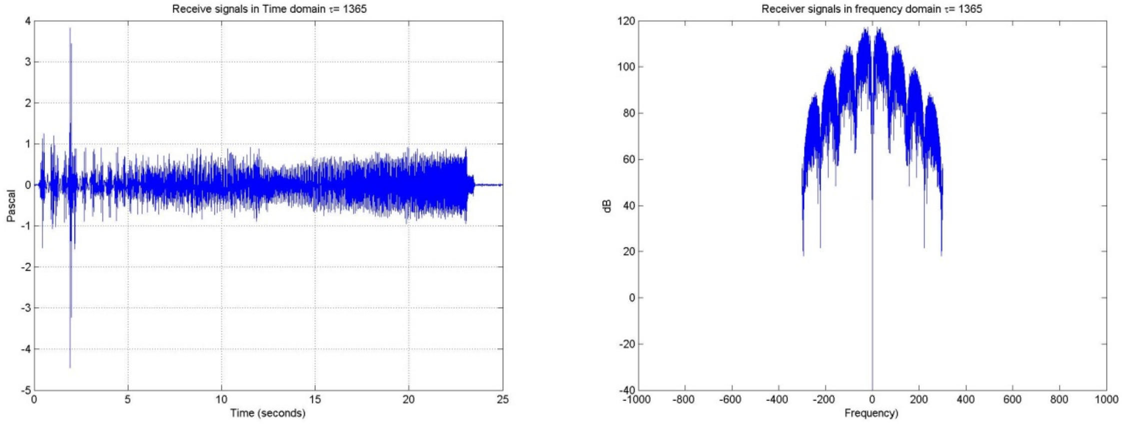
200 km



500 km



1000 km

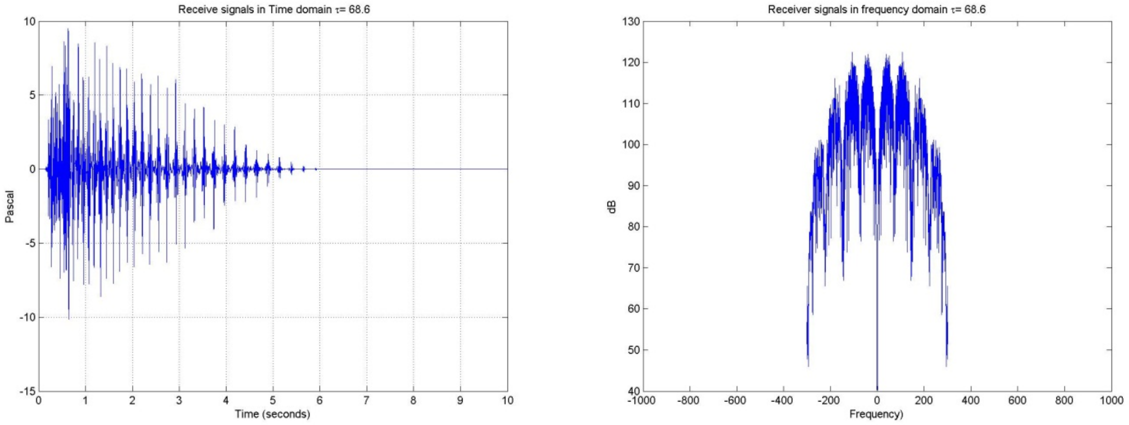


2000 km

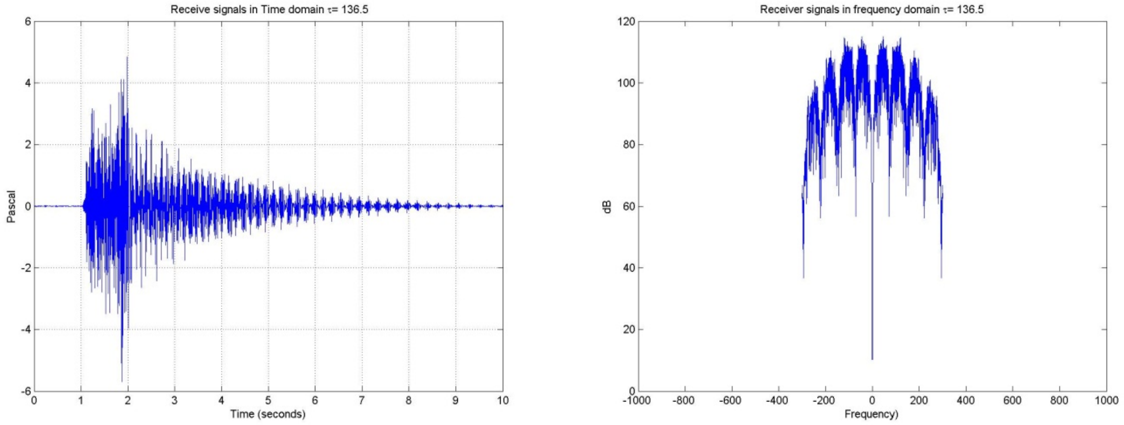
11.6.2 Depth 500 m

11.6.2.1 Station 715

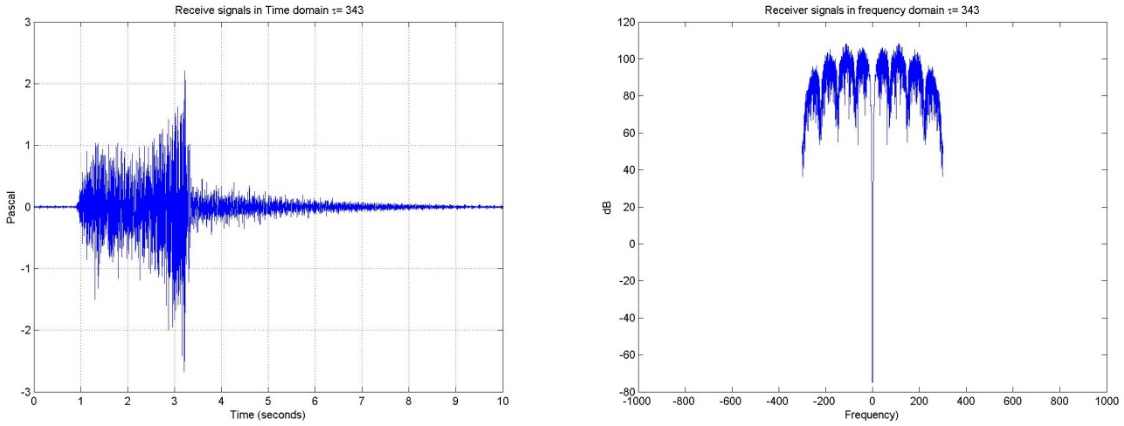
Receiver depth 10 m



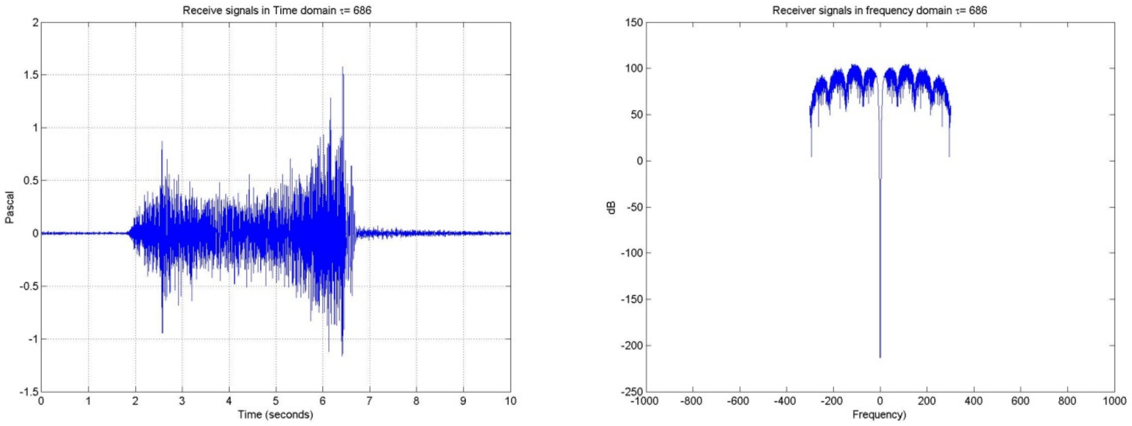
100 km



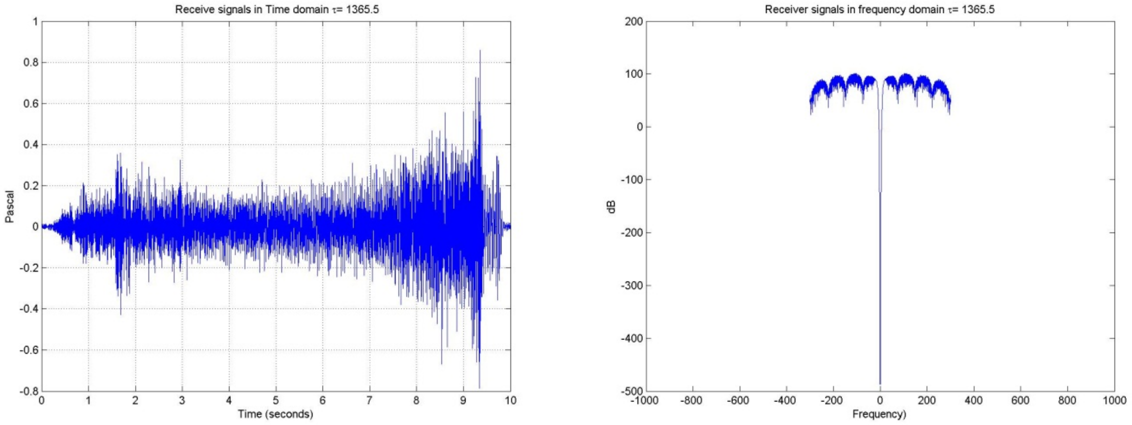
200 km



500 km

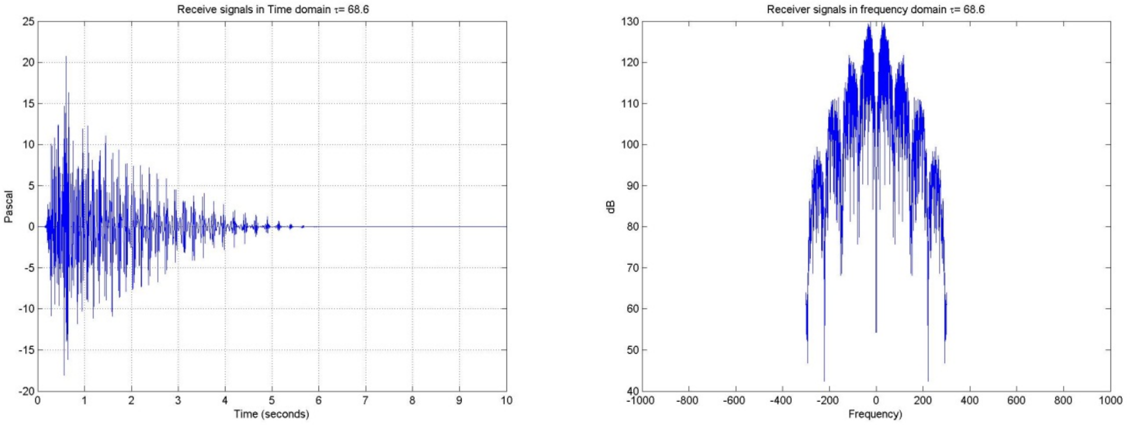


1000 km

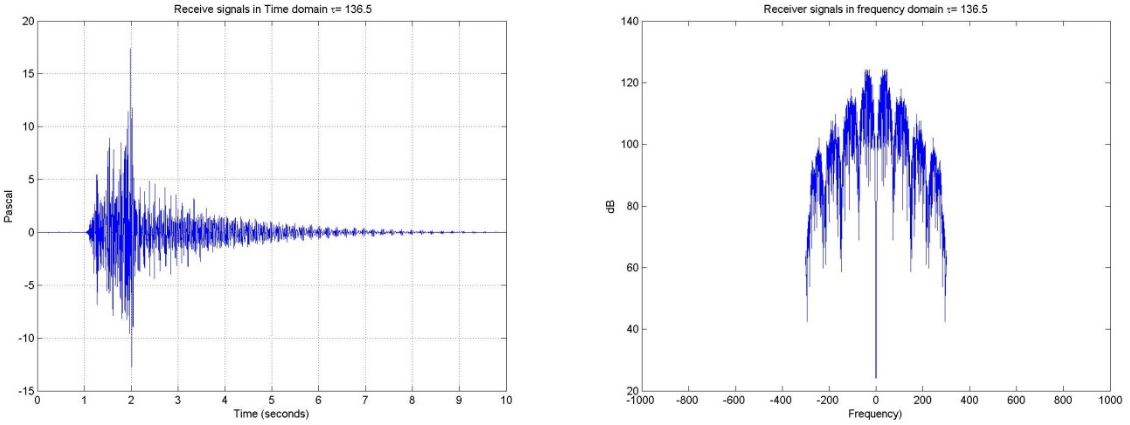


2000 km

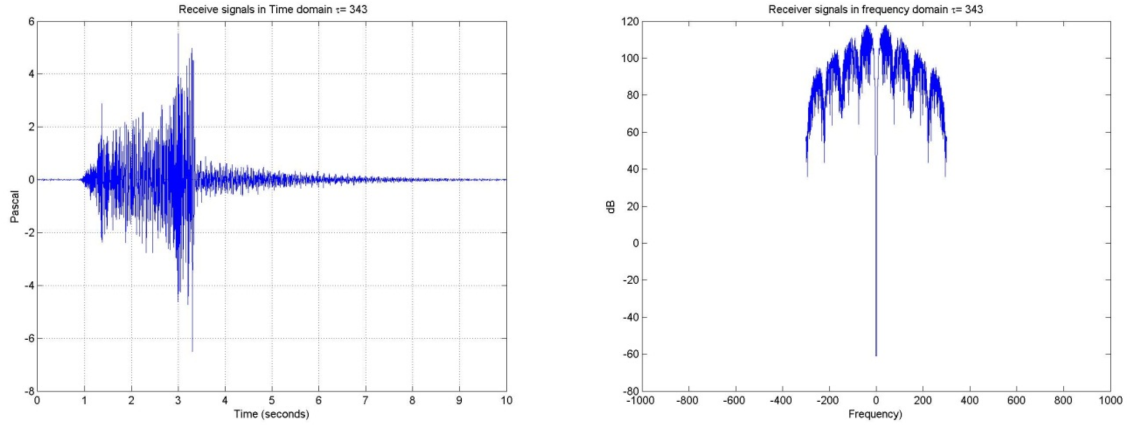
Receiver depth 50 m



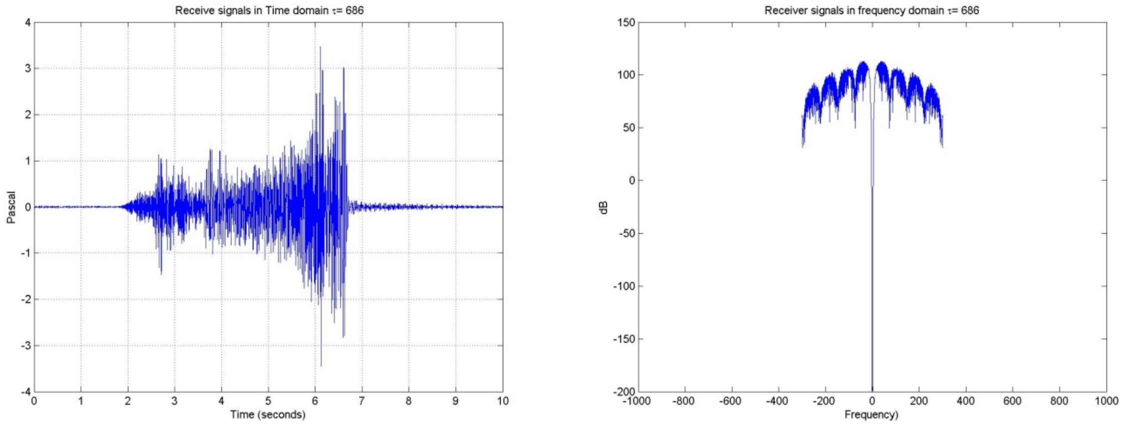
100 km



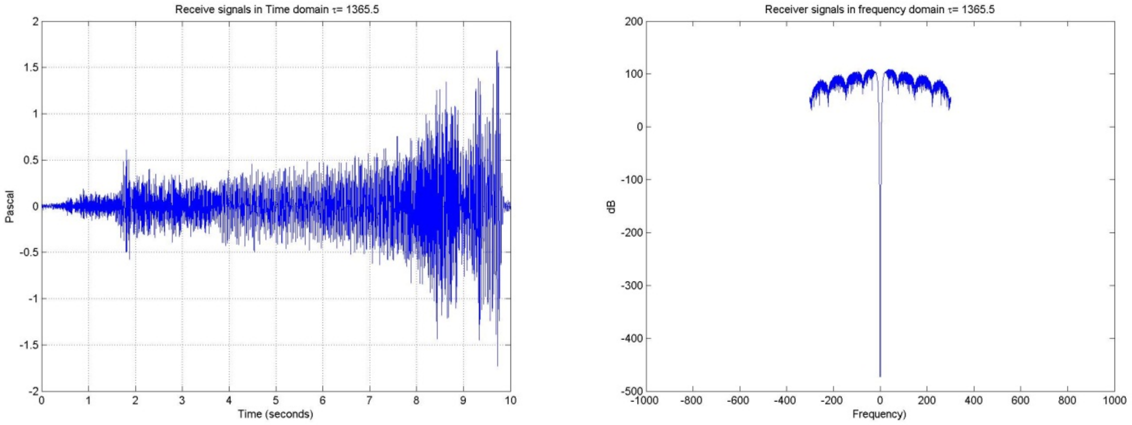
200 km



500 km

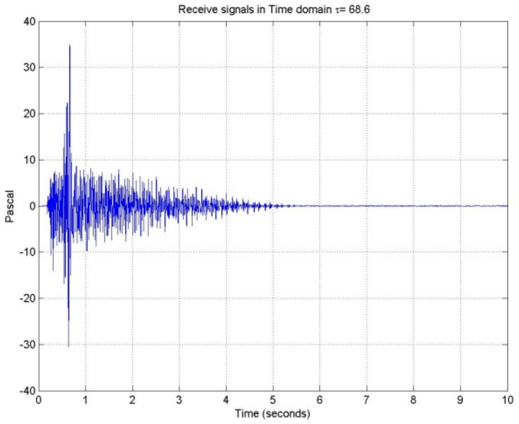


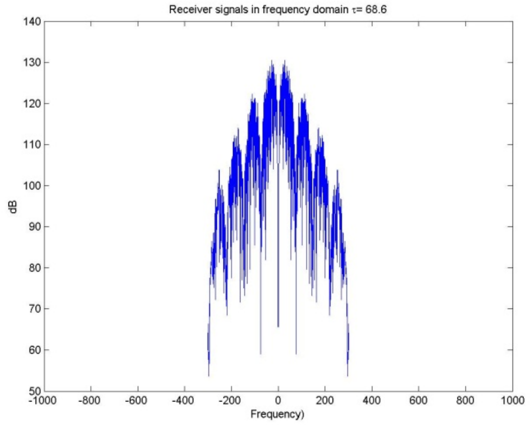
1000 km



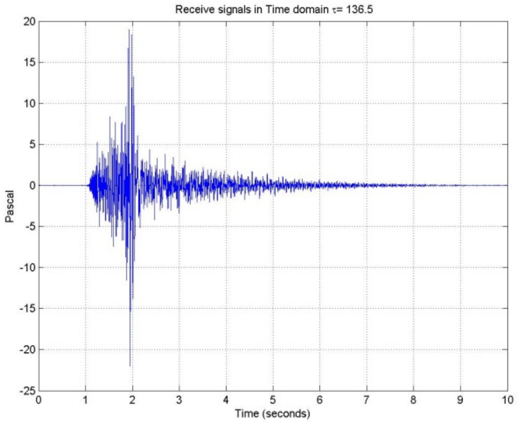
2000 km

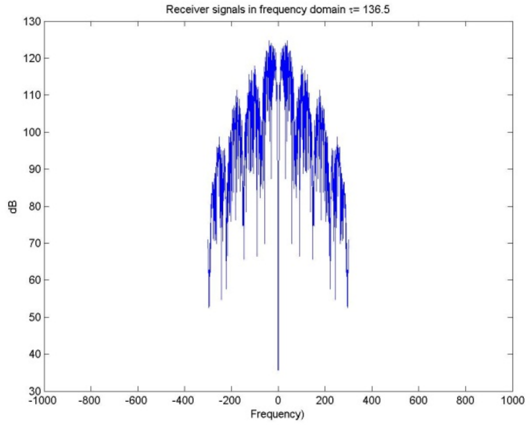
Receiver depth 200 m



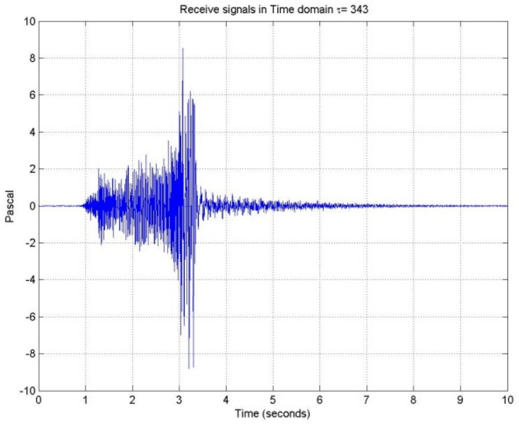


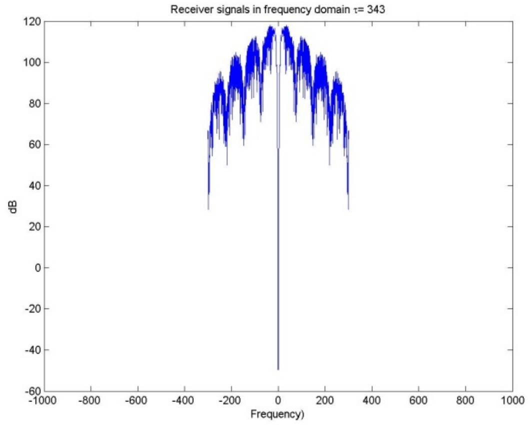
100 km



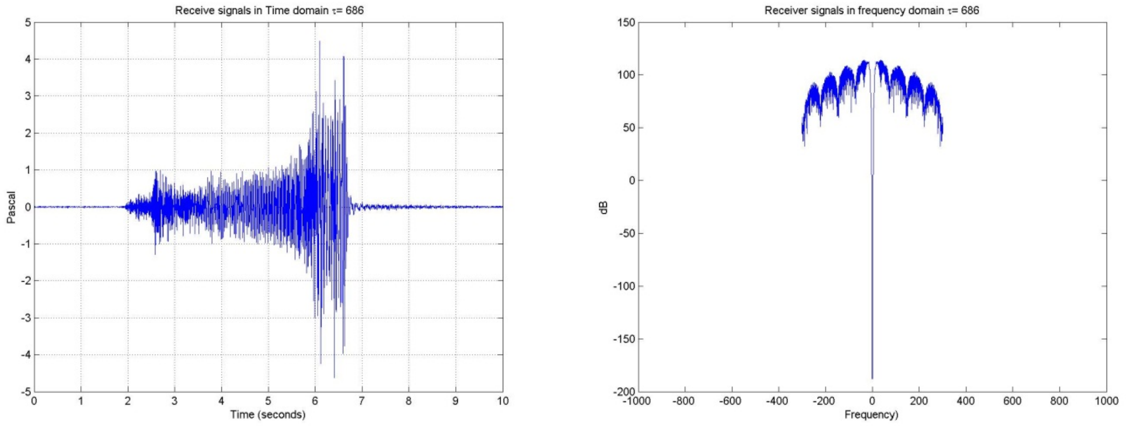


200 km

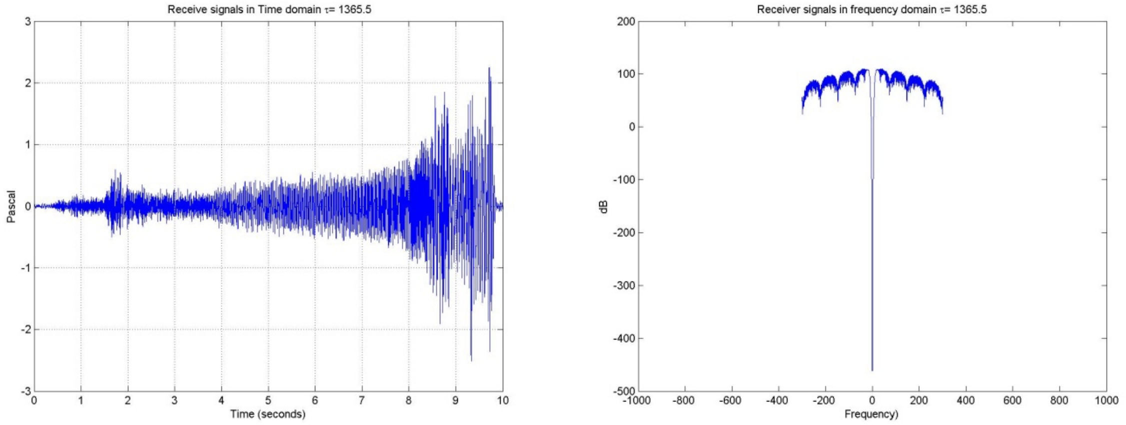




500 km



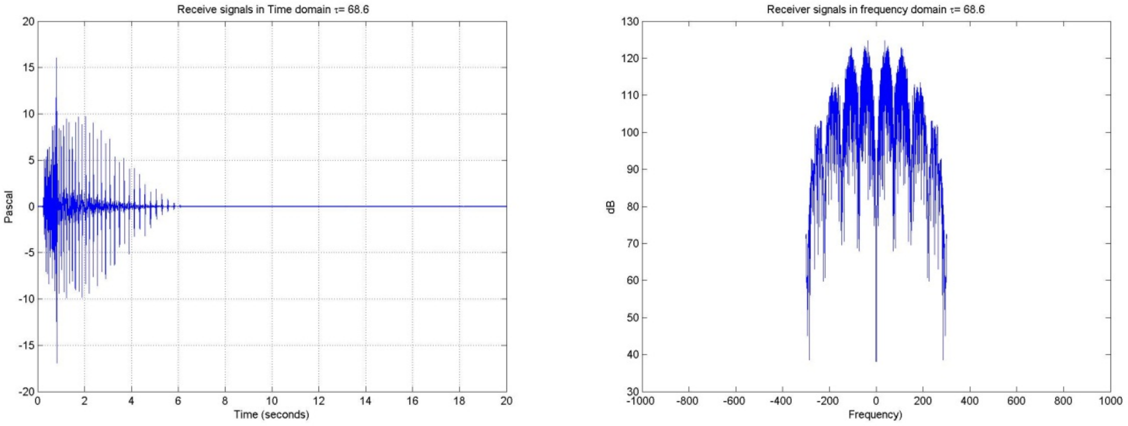
1000 km



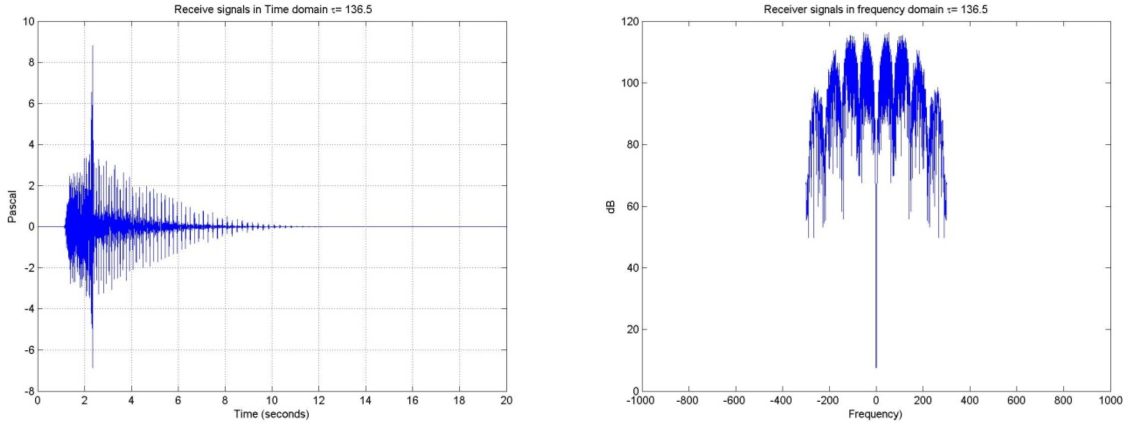
2000 km

11.6.2.2 Station 25

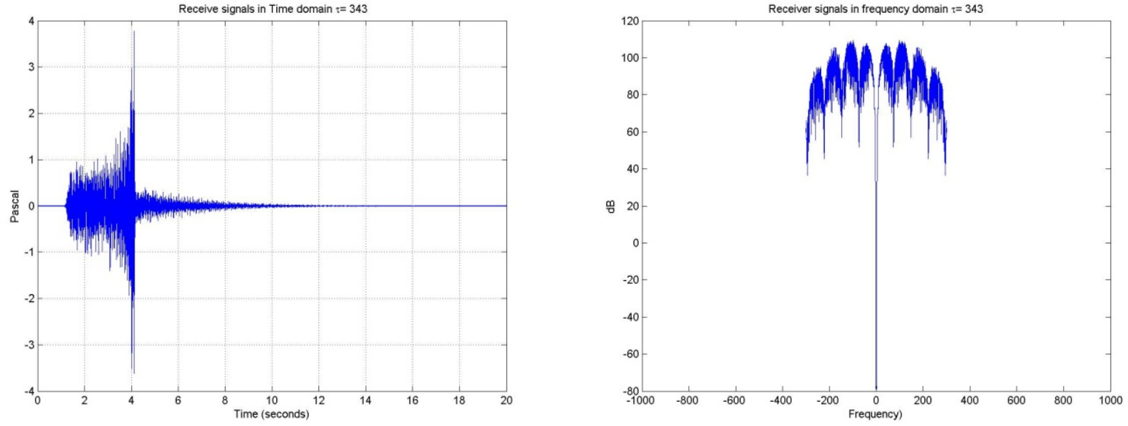
Receiver depth 10 m



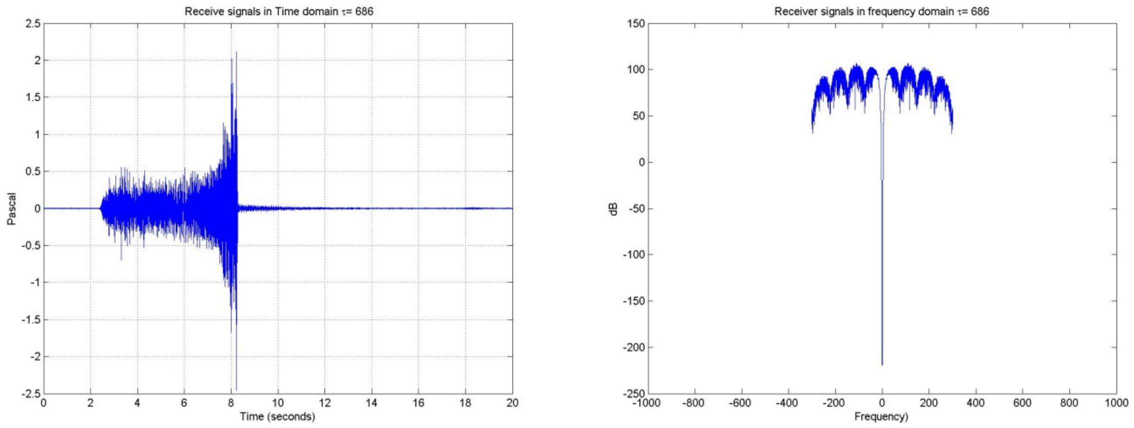
100 km



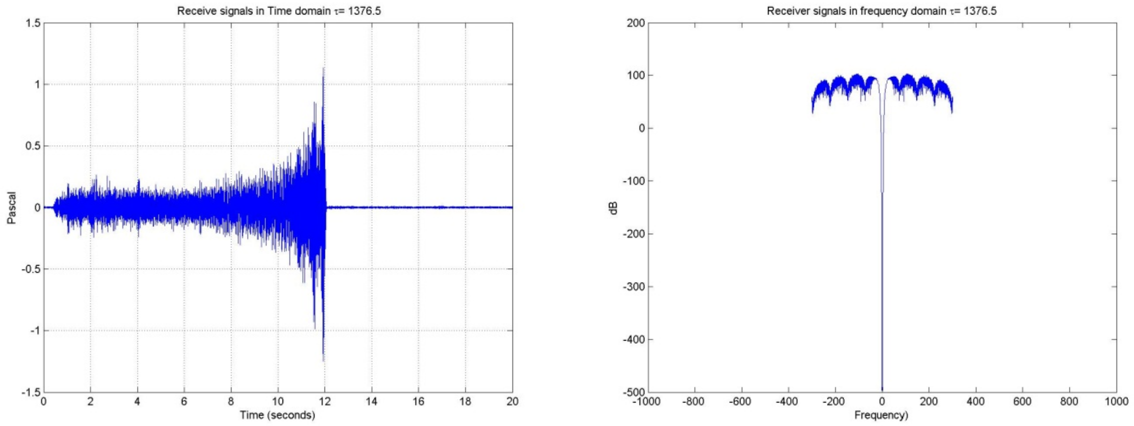
200 km



500 km

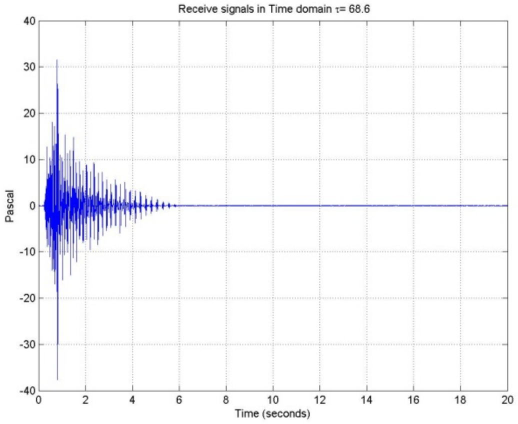


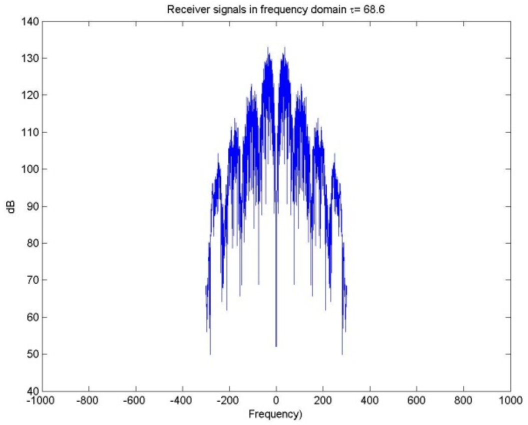
1000km



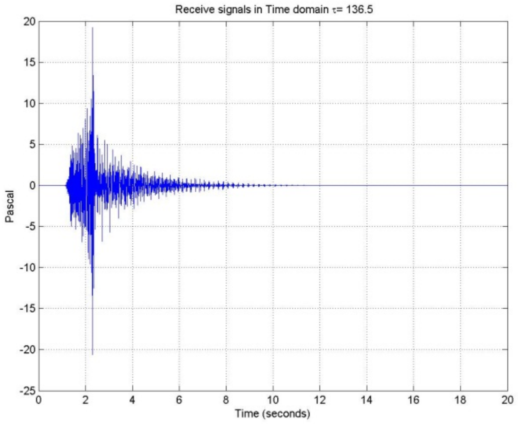
2000km

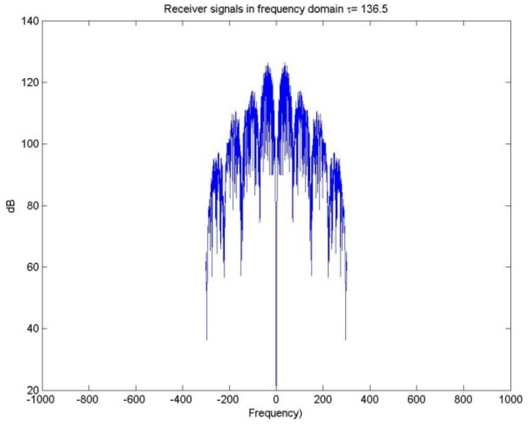
Receiver depth 50 m



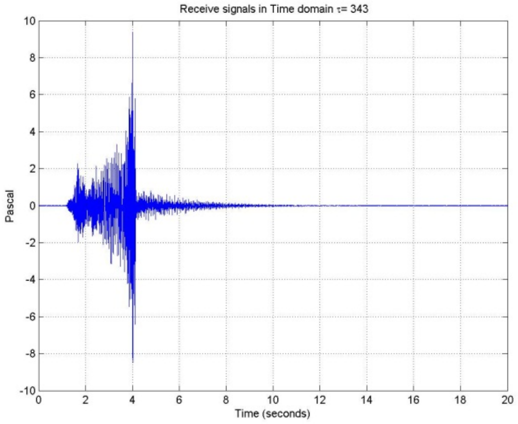


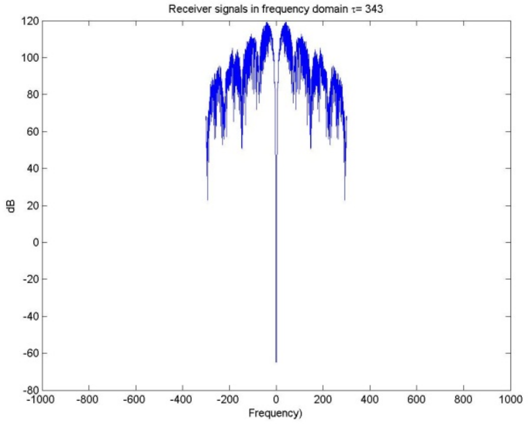
100 km



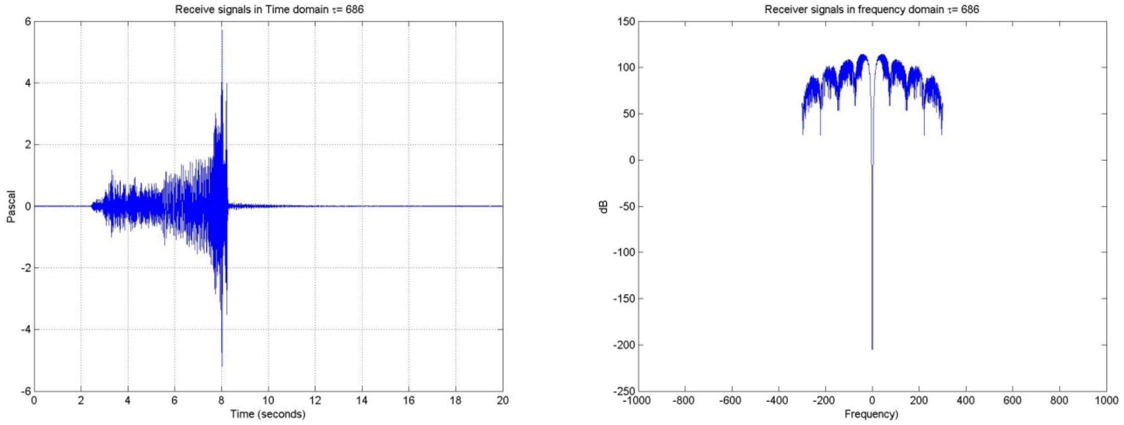


200 km

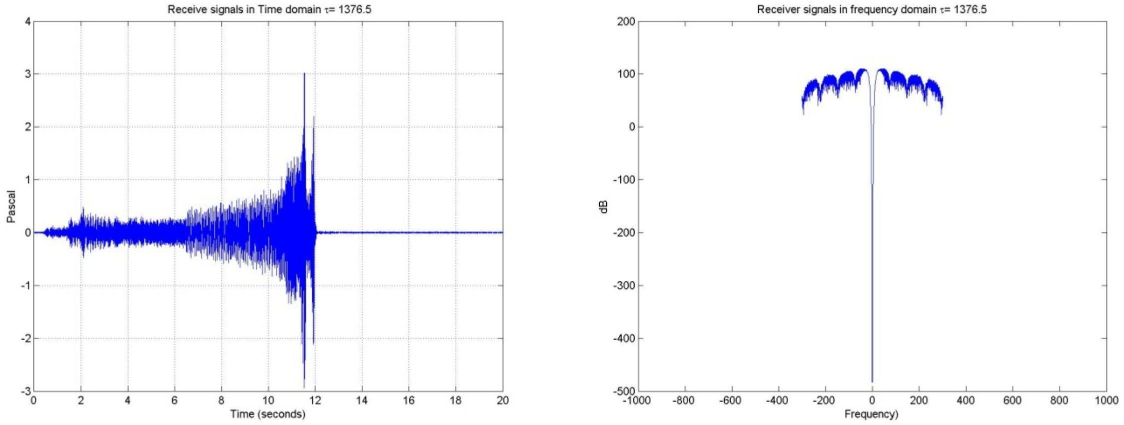




500 km

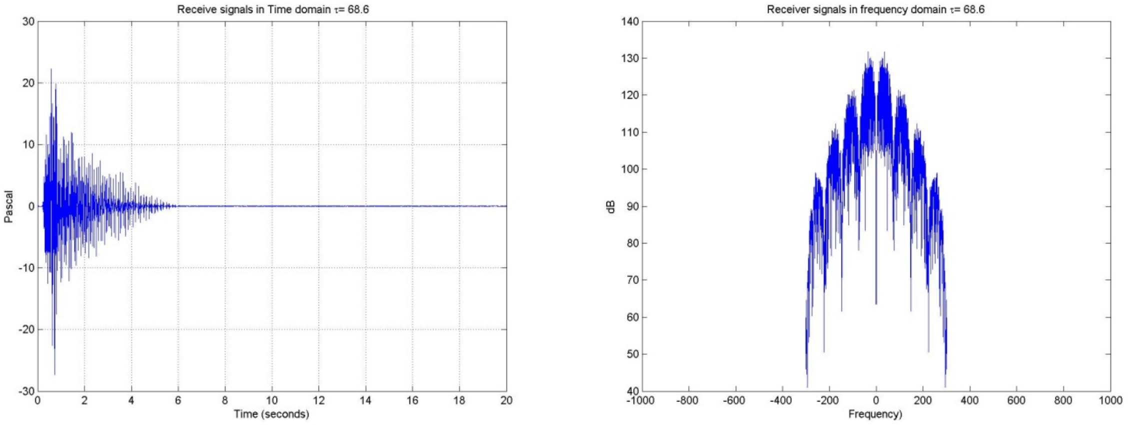


1000km

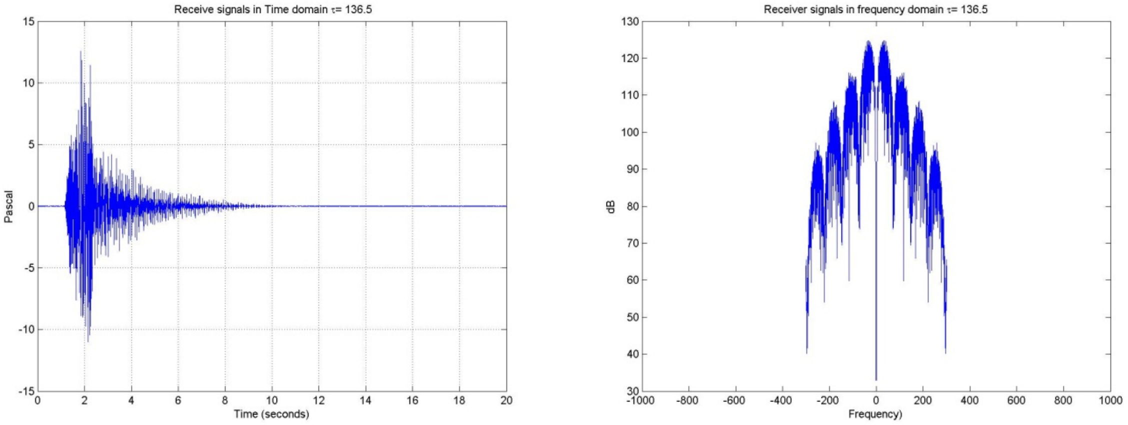


2000km

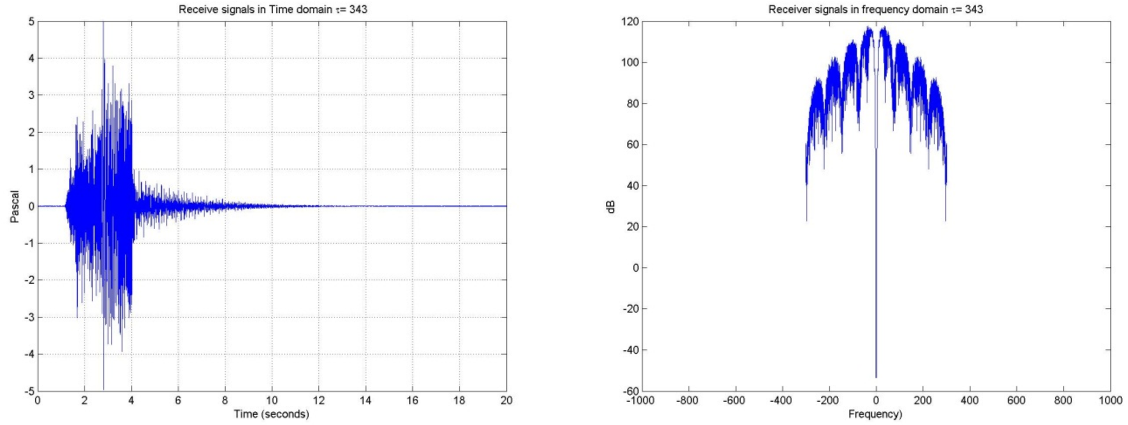
Receiver depth 200 m



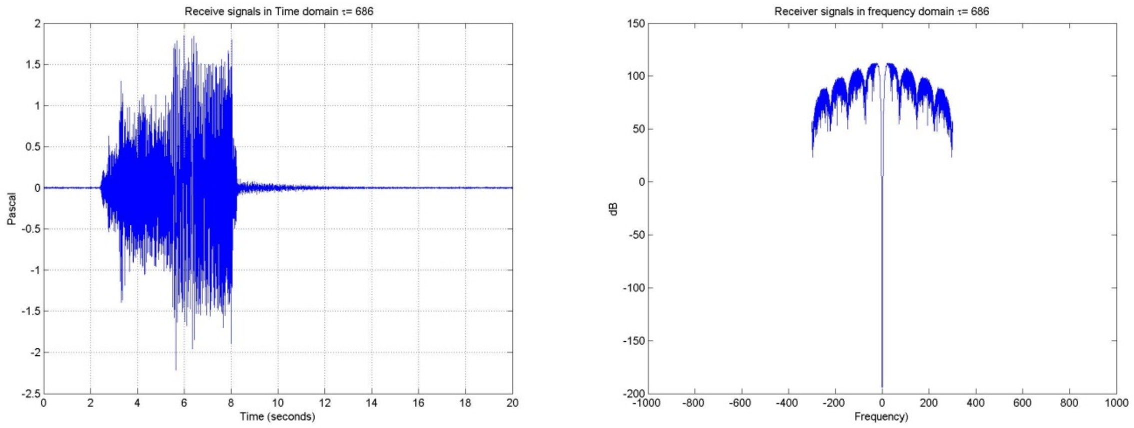
100 km



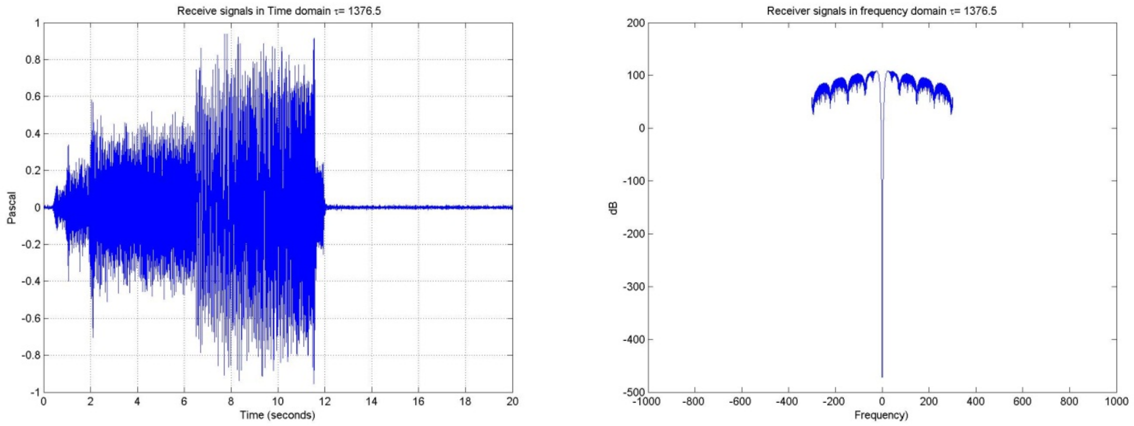
200 km



500 km



1000km



2000km

12 Appendix C: Results of masking modelling