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RUMBLE MEASUREMENT STRATEGY

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Jarl Johnsen
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8) ABSTRACT

This note is one of the deliverables of the RUMBLE program, which aims at developing methods for using operational sonars for measuring and estimating bottom parameters. These parameters are necessary for predicting sonar performance, but rarely available.
This note investigates the differences in some relevant backscattering models in order to define measurement strategies that can best parameterise the backscattering. The measurements will also be inputs to inversion methods being developed in RUMBLE that will be used to estimate the parameters needed as inputs to the chosen backscatter models. Several different measurements are proposed, and the observability of the parameters that can be extracted from the different measurements is commented upon.
Finally a set of measurements is proposed including recommended signals that the sonar should transmit.

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CONTENTS

RUMBLE MEASUREMENT STRATEGY

1 BACKGROUND

Bottom parameters are necessary inputs to acoustic models used to predict the sonar performance, and determine the sonar parameters that give the highest probability of detecting submarines in the area. Unfortunately these important bottom parameters have generally not been available to the navy, simply because there does not exist a simple and effective way of measuring them. Until now the bottom parameters needed for modelling have been measured using scientific equipment and special purpose sea trials. Even then, a substantial amount of data processing and analysis is needed to extract the relevant parameters.

RUMBLE attempts to make use of measured data from operational Low Frequency Active Sonars to extract the much needed bottom parameters. These sonars are often limited by bottom reverberation from close to long ranges, making it easy to quickly measure reverberation levels from large areas also when the sonar is in operational use. Unfortunately these reverberation levels are in principle only valid for the sonar operating in the chosen mode (signal type, frequency, depth) under the specific oceanographic condition that day.

It can be argued that Low Frequency Active Sonars are used for detecting targets at long ranges, and that it therefore is only is necessary to examine backscattering at small grazing angles in littoral, or shallow, waters. In this report we will investigate a more ambitious goal; will it be possible to measure enough parameters to determine not only the bottom backscattering strength, but also the most likely bottom type? And in that case, what should be the measurement strategy?

When acoustic models are used to predict sonar performance bottom backscattering models are needed to estimate the reverberation. The backscattering models need parameters that are specific for the bottom in the area. In order to extract these parameters inverse modelling must be performed, and this method is described in other RUMBLE reports. The method can simplistically be summarized as follows. An acoustic model is used to predict the measured reverberation level. The predicted and measured reverberation levels are compared. Many different parameters in the acoustic model are adjusted until the difference between the measured and predicted reverberation levels are within reasonable bounds.

The aim of the report is therefore to define measurements that can easily be modelled by simple propagation models. Measurement strategies for directly estimating some relevant parameters are also investigated, as it seems likely that the more parameters that can be fixed by direct measurements, the more accurate the bottom parameters can be found by inversion.

Chapter 2 investigates over what spread of grazing angles data must be collected in order to determine sufficient parameters to describe the bottom backscattering function for the area. Chapter 3 covers the question of which grazing angles can be expected as function of range. This leads to several possible measurements strategies that are evaluated. Finally the concluding chapter 4 recommends a set of measurements that covers a wide range of grazing angles.

2 BACKSCATTERING COEFFICIENTS

There are many models that describe backscattering from sea bottom. A collection of these is found in [1]. Some figures showing the backscattered energy as a function of grazing angle are repeated here and expanded in order to investigate their differences and define the parameters that need to be found.

2.1 Lambert-Mackenzie's rule

This rule is given by

$$\sigma_b(\theta) := \mu \cdot \sin(\theta)^n$$

Two parameters μ and n need to be determined. Figure 2.1 shows the result for the logarithmic value of μ equal - 27 dB and n= 1, 1.5 and 2. It is seen that for grazing angles greater than about 40 degrees the result is almost independent of n.
Accordingly in order to estimate the parameter n the backscatter should be measured at grazing angles smaller than about 20 degrees where the law starts getting more sensitive to this parameter. The value of μ should however, ideally be measured at grazing angles larger than 40 degrees where the backscattering strength is almost independent of n.

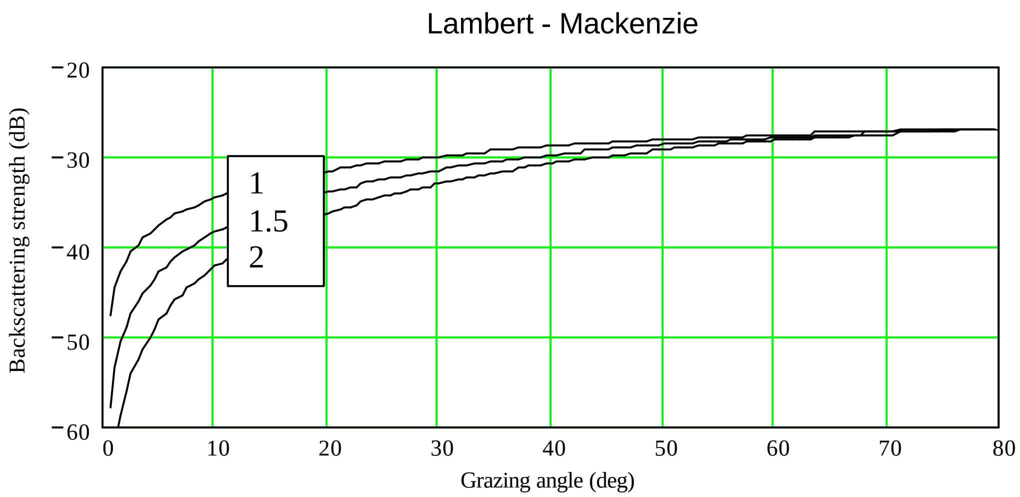

Figure 2.1 Lambert-Mackenzie rule for μ= - 27 dB and n=1, 1.5 and 2. The value n=2 corresponds to Lamberts rule.

2.2 Lamberts rule with threshold

Experience has shown that at small grazing angles Lambert-Mackenzie's law often shows too low levels. Therefore a threshold s_0 is introduced:

$$\sigma_b(\theta) := \sigma_0 + \mu \cdot \sin(\theta)^n$$

The result plotted in figure 2.2 allows us to make the following observations:

- The parameters cannot be individually determined unless the bottom backscattering can be observed over a wide window of grazing angles.
- The parameter n greatly influences the shape of the function at low grazing angles.

The importance of collecting backscattering data from several grazing angles, especially at low values can be shown by looking at the curves at 20 degrees, where the sets of parameters s_0 = -57 dB, n=1.5 give the same result as s_0 = -44 dB, n=1.5 which again is equivalent to s_0= -37 dB, n=2. In this case µ= - 27 dB in all curves. One can of course not expect to determine three parameters with one measurement, but the curves shows that including more measurements at higher grazing angles than 20 degrees do not help, as the different models here give the same result.

Also at grazing angles below 20 degrees there are potential problems, as several sets of parameters results in approximately same values as function of grazing angle all the way down to about 5 degrees. Accordingly the measurements at grazing angles smaller than about 5 degrees are needed to determine the threshold value.

This can be summarised as follows:

- Backscattering at grazing angles greater than 20 degrees are needed to determine µ.
- Backscattering at grazing angles less than about 5 degrees are needed to estimate threshold s_0
- Backscattering at grazing angles below 20 degrees needed to estimate n.

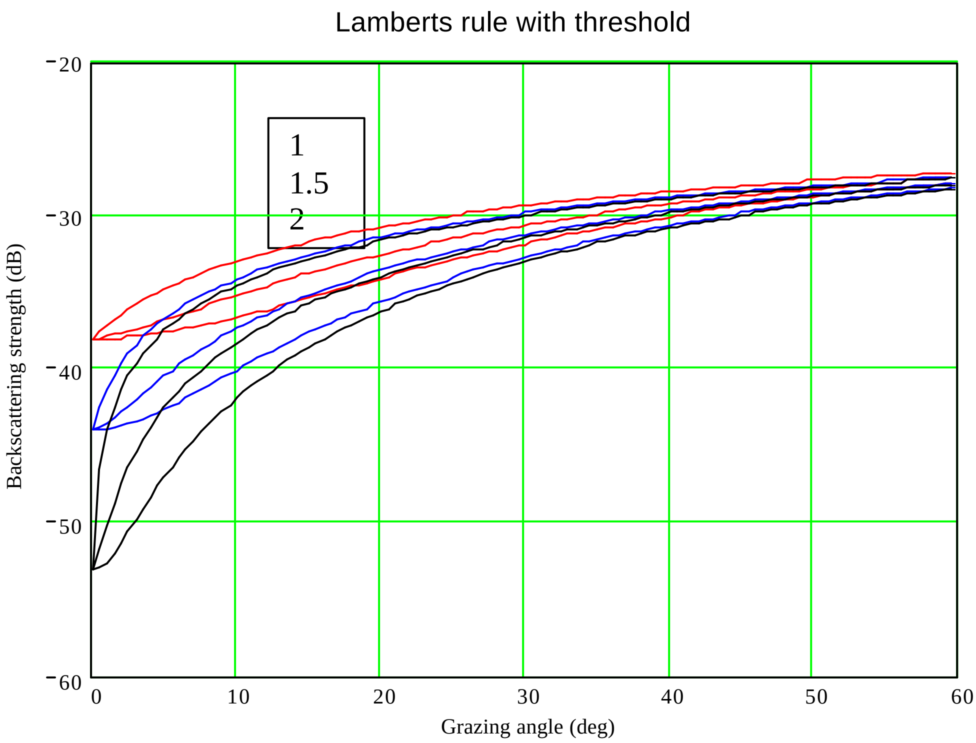

Figure 2.2 Lambert's rule with threshold= -37 dB (red), -44 dB (blue) and -53 dB (black). For each threshold value and n=1, 1.5 and 2. The value n=2 corresponds to Lamberts rule.

2.3 Del Balzo's rule

The model of Del Balzo ([1], [5]) is a modified Lambert's rule, which includes a correction at low grazing angles. The modification accounts for the effect mentioned above: that in some sediments there exists a scattering-strength plateau caused by scattering inside the sediment. But contrary to the previous section, the threshold is not a free parameter, but is connected to the Lambert constant. If this connection is correct only one parameter needs to be determined. In addition this parameter is related to bottom properties according to table 2.1. The rule is formulated as

$$\sigma_b(\theta) := \alpha(\phi) + \mu(\phi)\cdot\sin(\theta)^2$$

Sediment type	δ (mm)	ϕ	α (dB)	μ (dB)
Coarse Sand	0.500	1	-38	-23
Fine Sand	0.125	3	-41	-26
Silty Sand	0.044	4.5	-44	-29
Sand-Silt-Clay	0.016	6	-47	-32
Clayey Silt	0.008	7	-50	-35
Silty Clay	0.003	8.5	-53	-38

Table 2.1: Del Balzo's scattering rule [10]

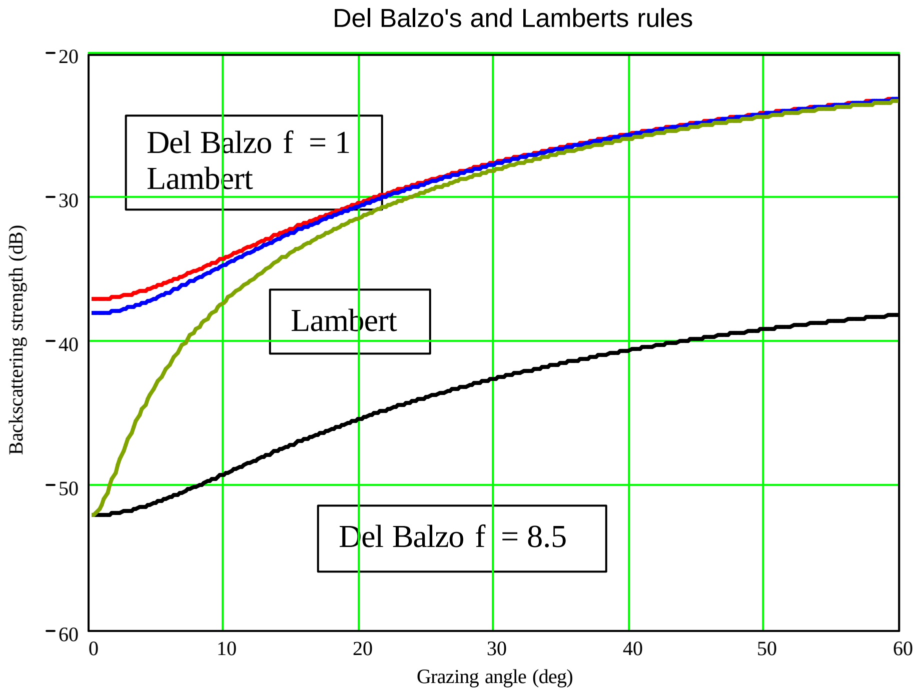

Figure 2.3 Comparing Lambert's and Del Balzo's rules
Blue: Lambert's rule with threshold = -39 dB, μ= - 23, n=2
Dark green: Lambert's rule with threshold = -53 dB, μ= - 23 dB, n= 2.
Blue: Del Balzo's rule for coarse sand, f = 1
Black: Del Balzo's rule for sand-silt-clay, f = 8.5

It is seen that Del Balzo’s rule behaves very different from the two previous rules based on Lamberts law. At low grazing angles it shows much smaller variation than the previous two models. In order to determine if Del Balzo’s rule describes the measured backscattering strength, it is necessary that the measurements covers both grazing angles at low values, i.e. below about 10 degrees and also high grazing angles, ideally above 30 degrees.

2.4 Modified Ellis rule

All the investigated previous rules show low scattering levels at normal incidence. This may be correct if the bottom is very rough so that the specular component can be neglected compared to the diffuse spreading of backscattered energy. For smoother bottoms Lamberts rule is not valid and Ellis ([1], [6]) has therefore included a special parameter to increase backscattering strength near normal incident.
If we include the threshold introduced in Lamberts rule for small grazing angles the modified Ellis rule can be written as:

$$\sigma_b := \sigma_0 + \mu \cdot \sin(\theta)^2 + \nu \cdot \left(\frac{1}{\sin(\theta)^4} \cdot e^{-\frac{\cot(\theta)^2}{2 \cdot \sigma^2}} \right)$$

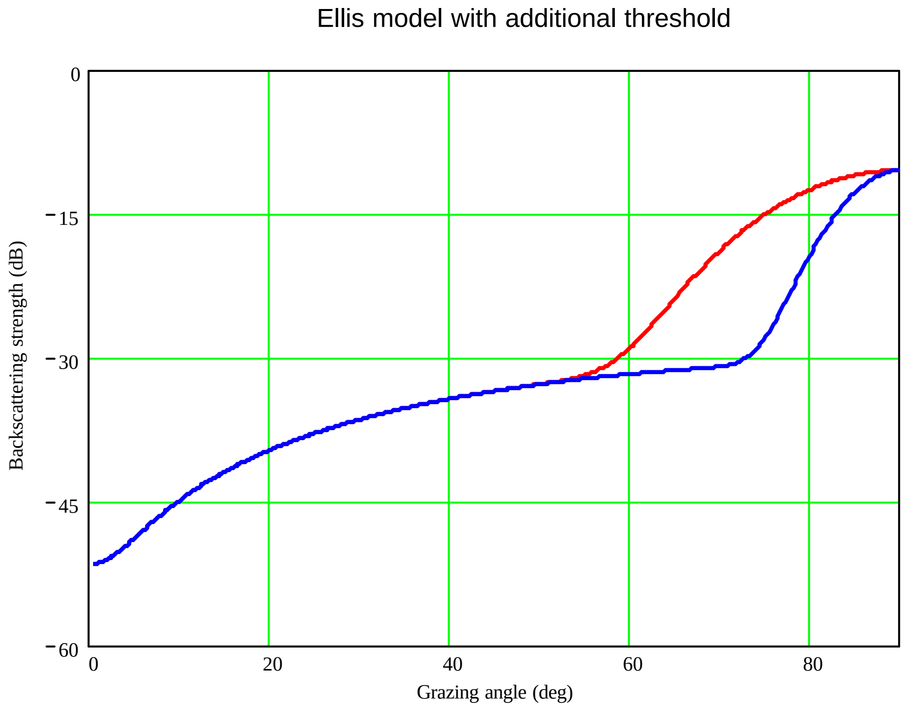

Figure 2.4: Ellis model with threshold s $_0$= -53 dB, μ= -32 dB and ?= -12 dB. The facet width s is 5° and 10°.

Four parameters are needed to define this model, compared to only two parameters if Lambert's rule with threshold was used. The two extra parameters define the backscattering strength at grazing angles near vertical. The value of the facet width, s , defines the grazing angle where the increase in backscattering strength starts and ? the backscattering strength at normal incidence. With the values shown in figure 2.4 Ellis model is equivalent to Lambert's rule with threshold for grazing angles smaller than 60 degrees.

2.5 Contributions from sediment inhomogeneities

For some bottom types the contribution from scattering within the sediment cannot be neglected compared to roughness scattering. As quoted from [1] the volume scattering may dominate at low grazing angles, and for soft sediments, the volume scattering may even dominate for all angles. It is therefore of interest to investigate if a model taking these features into consideration gives significant different backscattering results than the previous models for roughness scattering from the surface. We have chosen Novarini's model as an example. See [1] or [2] for details. The model assumes uniform distribution of scatterers inside the volume and also takes account of the rough boundary. Weak, single and isotropic scattering is assumed. The following bottom parameters are needed to define the model:

- Attenuation factor for compressional waves K_p.
- Scattering cross section per unit volume m_0.
- Compressional sound speed
- Density

The last two parameters may be defined as in table 2. The same parameters are used in Essen's physical model [4] examined in the next paragraph.

Sediment type	c_p (m/s)	ρ (kg/m^3)
Water	1500	1000
Rock	4000	2000
Gravel	2200	2000
Coarse sand	1830	2000
Fine sand	1750	1900
Silty sand	1650	1800
Silt	1610	1700
Silty clay	1550	1500
Clay	1515	1400
Fine clay	1490	1400

Table 2.2: Predefined seafloor classes [4]

The sound speed and density define the critical angle for refraction into the bottom. This angle is shown as a "notch" in the backscattering function shown in figure 2.5, which appears at for all bottom types except for fine clay and clay. The "notch" moves towards higher grazing angle as the bottom gets harder.

The level at higher grazing angles is controlled by the attenuation factor for compressional waves and the scattering cross section per unit volume m_0. One would expect that a bottom with a high scattering cross section would attenuate the acoustic field higher than a bottom with low scattering cross section and accordingly little scattered energy. In fact, by closer examining of Novarini's equations one finds that the backscattering function gives the almost identical results as long as the fraction K_p / m_0 is kept constant. The main difference is that the depth of the "notch" gets smaller for smaller K_p values, as seen in figure 2.6.

A 10 dB decrease in the attenuation factor K_p keeping m_0 constant gives a 10 dB higher backscattering level, and the same is found by increasing m_0 a factor of 10 and keeping K_p constant. The different bottom types influence the backscattering function mainly for grazing angles greater than about 5 degrees and below the grazing angle of the "notch". The backscattering level for grazing angles higher than the "notch" is fairly independent of the bottom type, almost completely determined by the bottom attenuation factor or bottom scattering cross section.

In order to classify the type of bottom according to this function, backscattering should be measured for grazing angles between 5 and 60 degrees.This may be possible using short range measurements where high grazing angles are observed. The method is described in chapter 3.2.

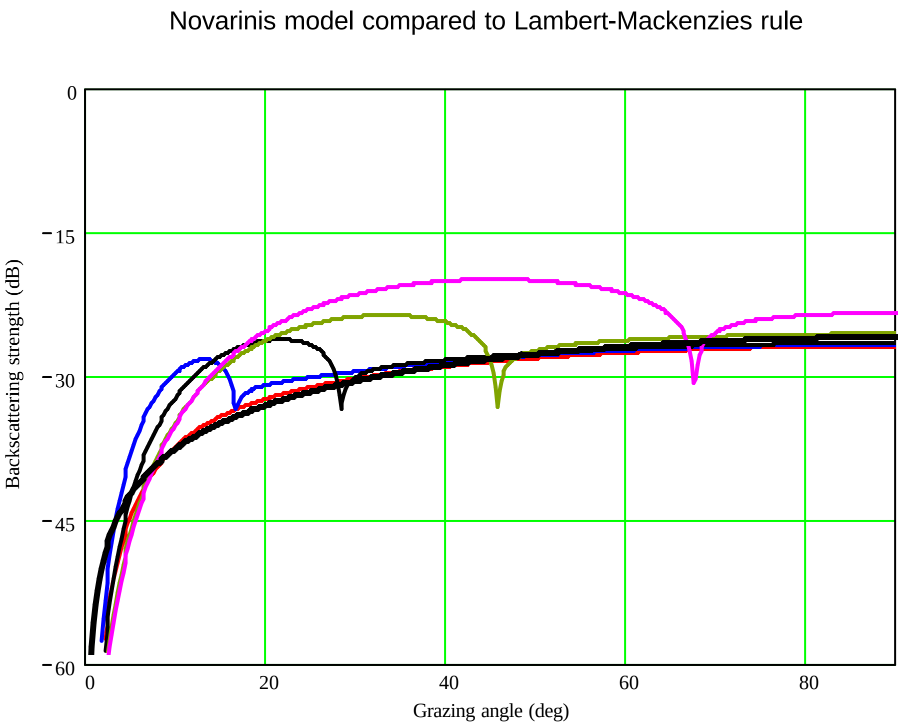

Figure 2.5 Novarini's model compared to Lambert-Mackenzie's rule.
Novarini's model is computed using the following parameters:
Scattering cross section per unit volume m_0 = 0.00004 for all bottom types
Attenuation factor for compressional waves = 0.00004 for all bottom types
Red: fine clay
Blue: silt
Black: fine sand
Dark green: gravel
Magenta: rock
Lambert-Mackenzies rule is computed with μ= - 27 dB and n= 1.5, and is seen as the smooth black curve almost covering Novarini's model for fine clay.

If the “notch” can not be determined, the reason can be that the attenuation in the bottom is so high that the “notch” can not be observed, as seen in figure 2.6, or the fidelity of the measurements is not enough to bring it out.

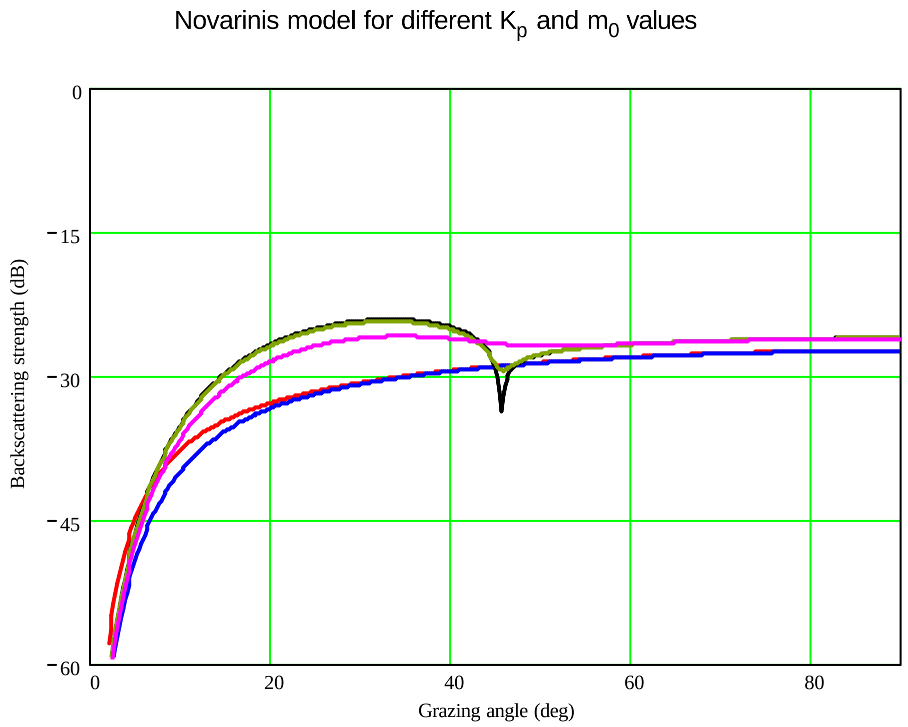

Figure 2.6 Novarini’s model with different K_p and m_0 values
Novarini’s model is computed using the following parameters:

Red: fine clay	K_p and $m_0 = 0.00004$
Blue:fine clay	K_p and $m_0 = 0.004$
Black: gravel	K_p and $m_0 = 0.00004$
Dark green: gravel	K_p and $m_0 = 0.0004$
Magenta: gravel	K_p and $m_0 = 0.004$

2.6 Essen’s physical model for roughness scattering

Essen [1] and [4], describes a simple first order model for scattering from a rough seafloor. The seafloor parameters involved are the roughness spectrum of the seafloor, and the sound velocities and densities of the water and sediment. If the backscattered data fits this model it will therefore in principle be possible to read out the most likely bottom type. The roughness spectrum is given by

$$F(\theta) := \frac{1}{2\cdot\pi\cdot(2\cdot k\cdot\cos(\theta))}\cdot G_0\cdot(2\cdot k\cdot\cos(\theta))^{-n}$$

where G_0 controls the level of the backscattering curve without changing the shape, and n the slope, while k is the wavenumber in water. For n = 3 the backscattering curve is independent of frequency, as other parts of the model cancels the frequency dependence of the roughness spectrum. In this paper the approximate center frequency 1500 Hz is chosen. The indicated standard values are $G_0 = 0.04$ and n between 2 and 4. If G_0 is increased by 10 the whole backscattering curve is shifted 10 dB up, n = 2 results in less increase in backscatter level as a function of grazing angle compared to n = 4, as shown in figure 2.7

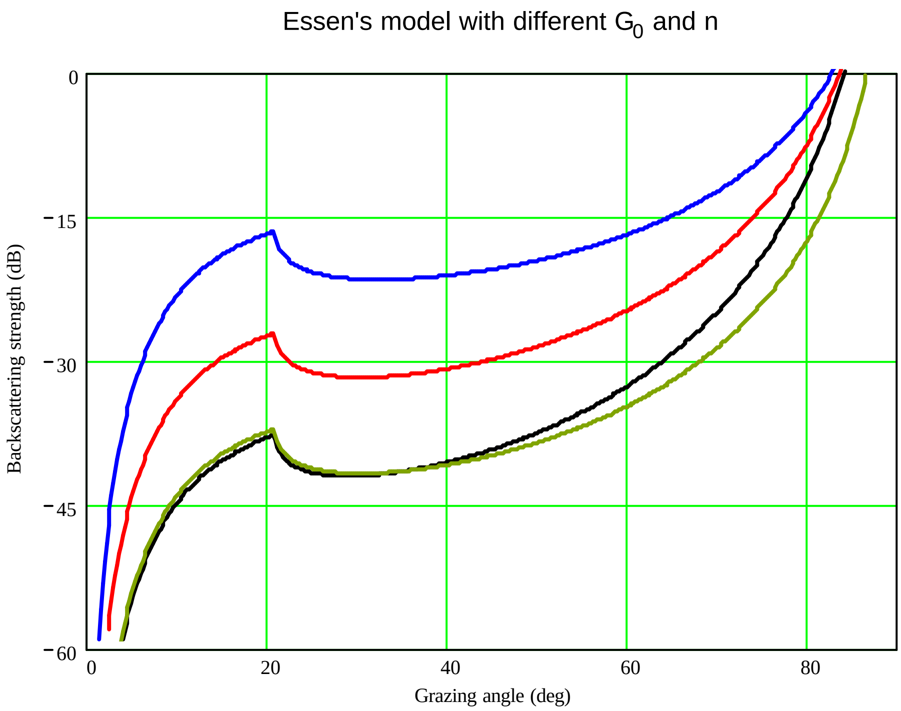

Figure 2.7 Essens model for different values of roughness spectrum and exponential dependence. Bottom is silty sand with parameters according to table 2.2., sound velocity 1650 m/s, density 1800 Kg/m^3.
Blue: n = 2, $G_0 = 0.04$
Red: n = 3, $G_0 = 0.04$
Black: n = 4, $G_0 = 0.04$
Green: n = 3, $G_0 = 0.004$

Figure 2.8 compares Essen's model with Ellis and Novarini's models for the same type of bottom. They show similar results for backscattering angles up to about 60 degrees with the chosen parameters for roughness spectrum strength, scattering cross section per unit volume and attenuation factor for compressional waves. These parameters change the level of the curve, but very little the shape. If the shape of the curve can be deducted from measurements, it seems like both models can be used to define a bottom type if the values in table 2.2 can be trusted.

Essen's pertubation model for roughness scattering, Novarini's model for volume scattering and Ellis model

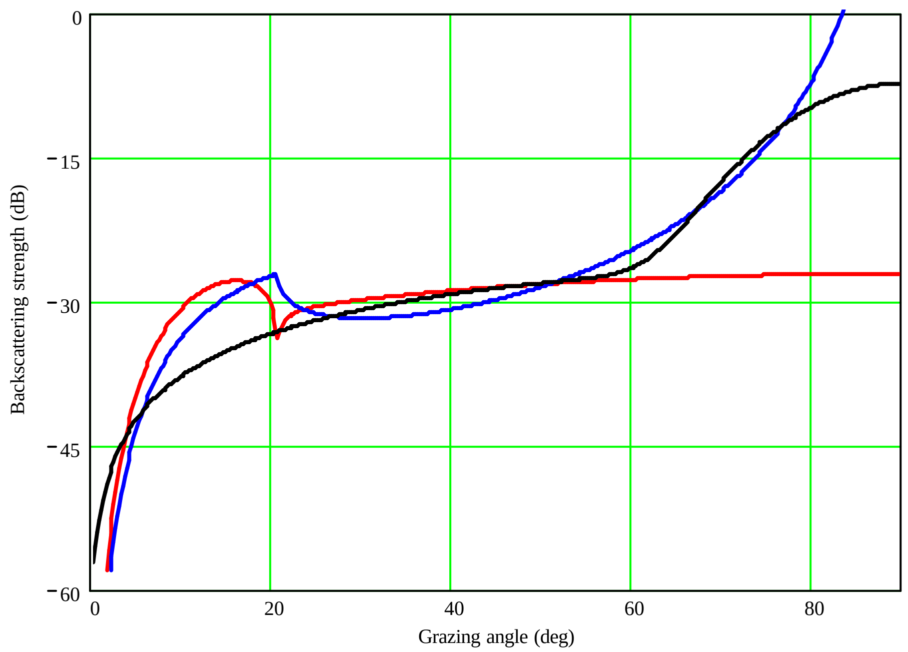

Figure 2.8 Comparison of three models. Silty sand (soundspeed 1650 m/s and density 1800 kg/m^3) is common parameters for Essen's and Novarini's models.
Blue: Essen's model with roughness spectrum strength = 0.04 and spectral exponent = 3
Red: Novarini's model with K_p and m_0 = 0.00004
Black: Ellis backscattering model with the following parameters: s_0= -59 dB, µ= -27 dB and ?= -8 dB, n=1.5 and the facet width s = 9°.

If the backscattering strength follows a more gradual decrease with for small grazing angles, like Ellis model in figure 2.8 this indicates a different and softer bottom than silty sand. From figure 2.6 it is seen that fine clay would fit Ellis model better. Both Essen's and Novarini's models therefore seem to cover a wide range of bottom types, and give comparable results to non physical models like Ellis and Lamberts rules for grazing angles less than about 60 degrees. Figure 2.9 shows Essen's results for all bottom clsses in table 2.2 when the roughness spectrum strength and spectral exponent are kept constant.

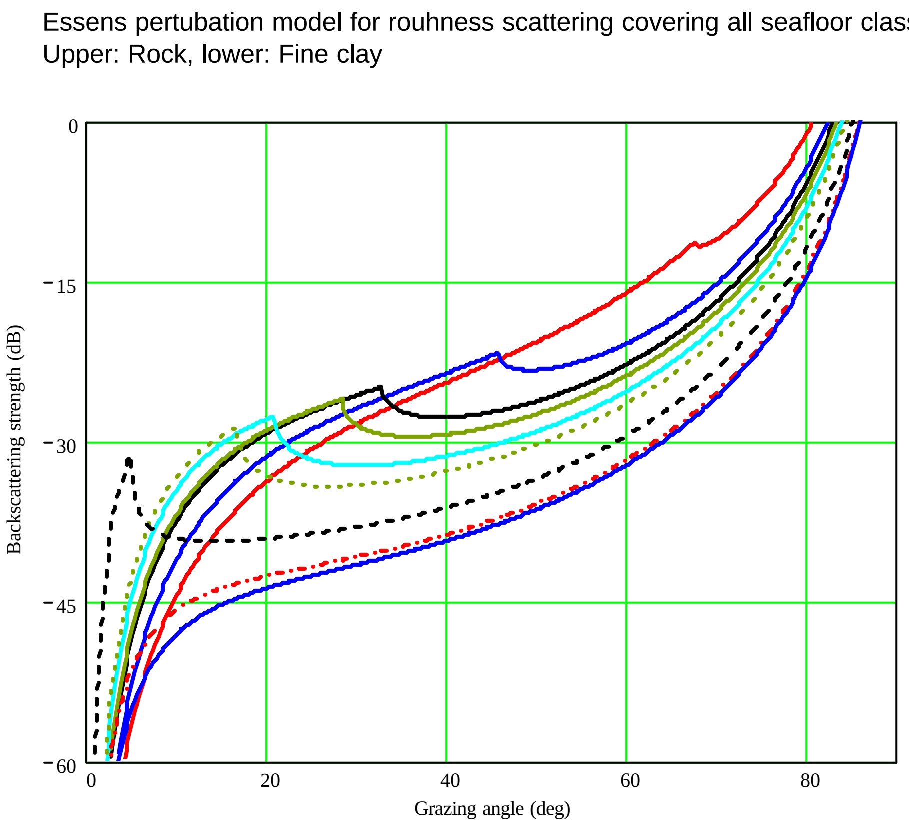

Figure 2.9 Essen’s model for all seafloor classes defined in table 2.2 with roughness spectrum strength = 0.04 and spectral exponent = 3. The bottom blue curve represents fine clay, while the upper red curve represents rock.

2.7 Relevant measurements

Reference [1] includes, in addition to the models quoted in this paper, several other models that use more physical information about the bottom, like roughness, to give backscatter values. All the models seem to require measurements at low and medium grazing angles in order to be defined accurately, i.e. from near horizontal to about 50 degrees.

Ideally the measurements should give enough data to define which of the many backscattering models are valid for the area and the parameters needed for using them. A general strategy may therefore be summarized as fo llows:

- Measure backscatter below 10 degrees, ideally at as low grazing angle as possible to define a possible threshold value needed in some models..
- Measure backscatter at about 25 to 50 degrees to define the smooth variation away from the threshold.
- Measure backscattering between 5 and 50 degrees to define the bottom rougness. If the data fits physical models like Essen’s model ([1], [4]) the bottom type can be determined.
- Backscatter measured at grazing angles above 50 degrees may follow a different “law” and do therefore not necessarily give information on backscatter at low grazing angles.

We have now determined at which grazing angles we need to measure backscattering, or reverberation. The question that now needs to be addressed is: at which grazing angles can we measure reverberation in littoral waters?

3 MEASUREMENT STRATEGY

This chapter investigates different strategies that can be used for measuring backscatter as function of grazing angle with the limitations given by the sonar systems used in RUMBLE experiments.

3.1 Relevant grazing angles from operational Low Frequency Active Sonars

Typically these sonars transmit omnidirectional in the horizontal plane and due to only 2 to 4 vertical transducer sections the vertical beamwidth is wide. The bandwidth is about 1 kHz, and the pulse length during ASW operations is typically about 5 seconds, which is the pulse length used during the first RUMBLE sea trial.

In littoral waters the wide vertical transmit beam results in strong bottom-surface reflections that gradually die out after the transmission is finished. These reflections can be used for measuring the backscatter if the electronics in the array and subsequent processing does not saturate. The shortest range is therefore about 4000m when a 5 second signal is transmitted. In reality the shortest range is even further because the array used in the RUMBLE experiment used 12 bit A/D converters and therefore probably saturate for some period after the transmission. Figure 3.1 (copy of Figure 3.1: Broadside beam in leg 5) from [3] seems to indicate that saturation effects occur until a time after transmission equivalent to echoes from targets about 4 nautical miles or 7 km from the array.

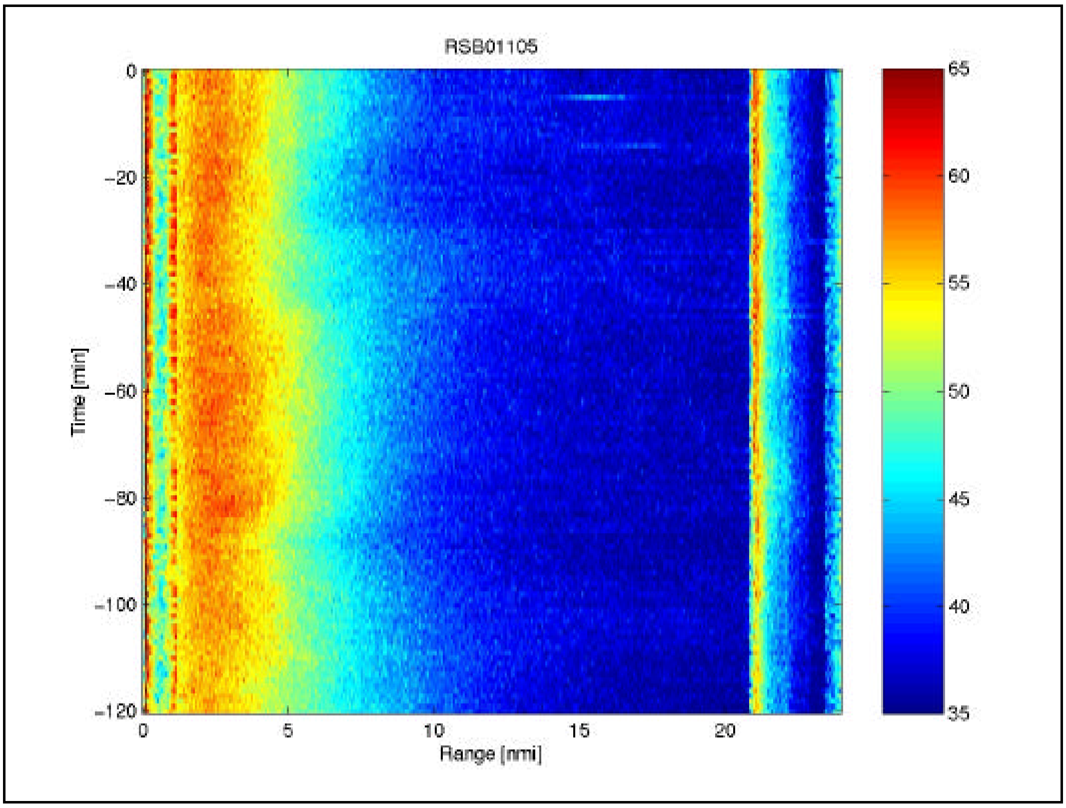

Figure 3.1 Broadside beam in leg 5 from RUMBLE first sea trial in Vestfjorden

The Norwegian LYBIN ray trace sound propagation model has been used to calculate the backscattered energy as a function of grazing angle. The distance between the rays was about 0.072 degrees. The source and receiver array were towed at 50 m depth, the water depth was 250 m. Sound speed profile typical for Vestfjorden in May/June is shown in figure 3.2.

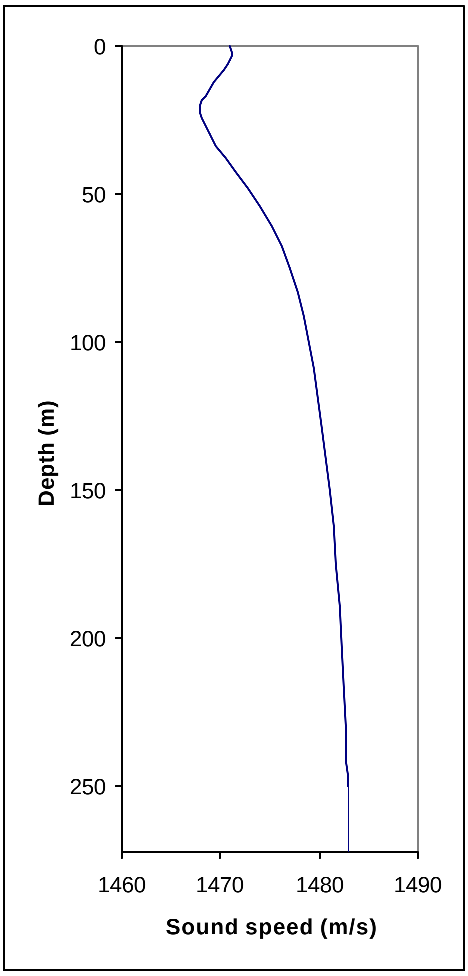

Figure 3.2 Typical sound speed profile in Vestfjorden during May/June.

Figure 3.3 shows the grazing angle of the energy along the bottom when a short “impulse” is transmitted by the source. After propagating 200 m the energy hits the bottom vertically and then it moves away from the transmitter while the grazing angle reduces from 90 degrees to about 2 degrees after 5000 m. Immediately after the first signal reaches the bottom, the energy that is reflected at the surface has traveled 300 m and reaches the bottom for the first time. A bit later the signal that has been reflected off the bottom traveled vertically back to the surface and then reflected vertically down reaches the bottom after traveling 200+250+250=700 m. Shortly afterwards the signal that was first reflected off the surface and then traveled the same path arrives at the bottom. This surface-bottom “ringing” decays with time due to attenuation and the general spreading loss and absorption. All these signals spread out with time and reach the bottom with lower and lower grazing angles as shown in figure. 3.3.

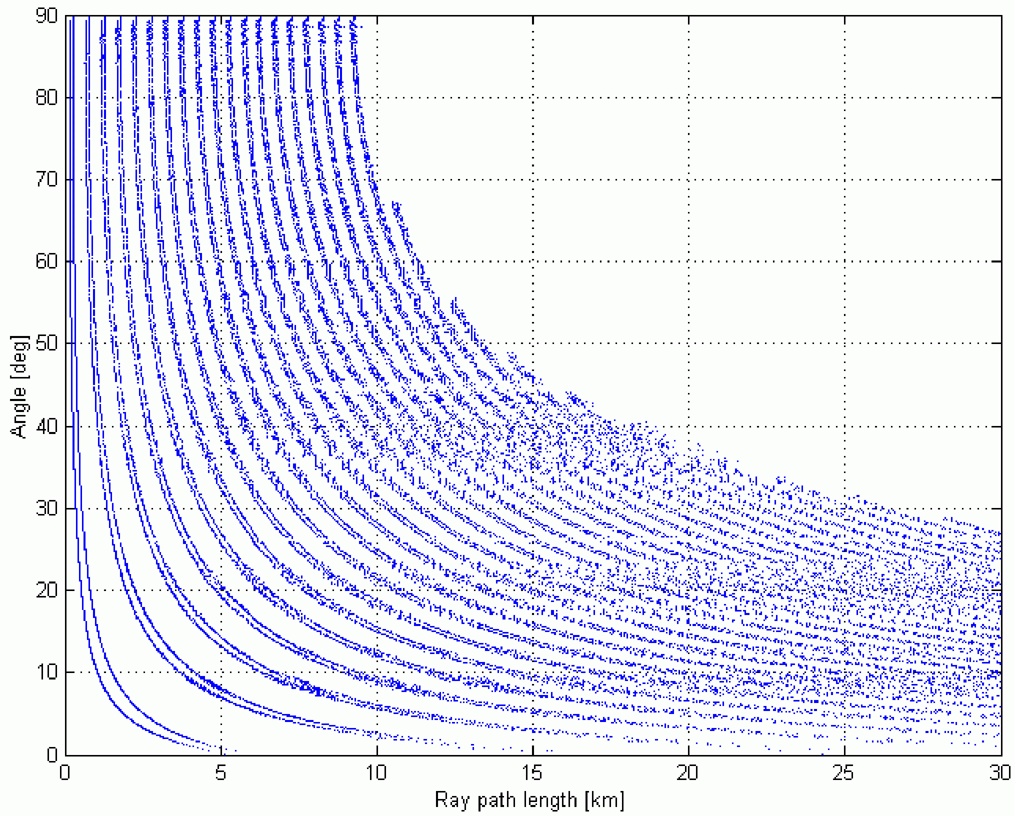

Figure 3.3 Grazing angle at the bottom as function of traveled distance.

After the direct signal has traveled 2000 m its grazing angle is about 5 degrees. At the same time surface and bottom reflected signals arrives at the bottom closer to the source with the following approximate grazing angles: 7, 20, 22, 36, 40, 58 and 62 degrees. As the time progresses more and more signals arrives at the bottom with higher and higher grazing angles. Even at long ranges, energy hits the bottom with grazing angles from near 0 degrees to almost 30 degrees.

The higher the grazing angle the more reflections from the surface and bottom the signal has experienced at a given distance, each introducing reflection loss dependent on the surface conditions and bottom type. In figure 3.4 the attenuation for each ray path is shown. It must be noted that the horizontal axis shows the length of the ray, and not distance from the source. So a 10 km long ray may only have reached a short distance from the source, because it has been traveling almost vertically between surface and bottom. This ray will have a large attenuation.

Another 10 km long ray may have traveled almost horizontally and experienced low attenuation.

If we, for the sake of argument, assume that all rays that are attenuated 12 dB or more than the ray with lowest attenuation at each range are of little importance, about five bundles of rays are relevant for all ranges longer than 5 km. The relevant ray bundle with the highest grazing angle is shown in figure 3.5 as function of range.

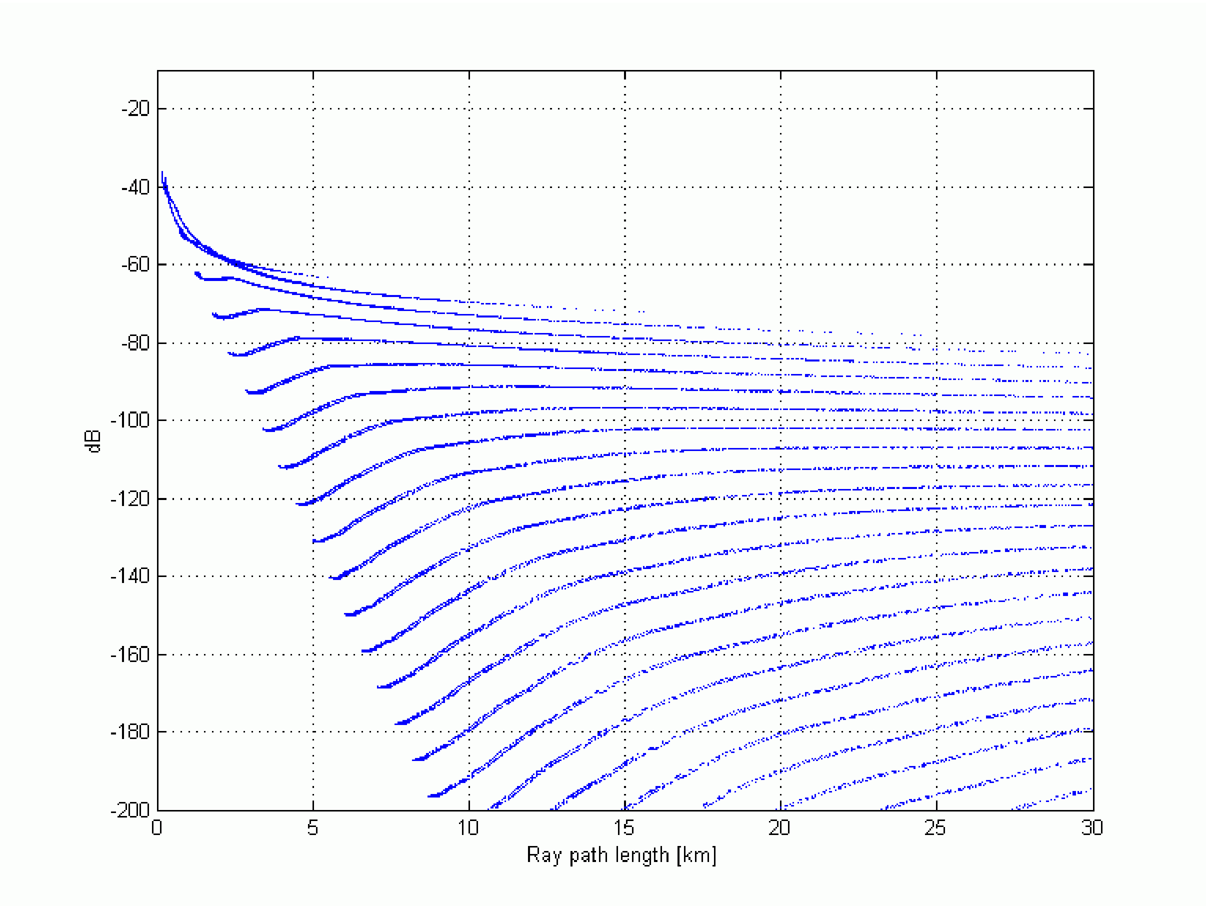

Figure 3.4 Attenuation for each ray as function of ray length

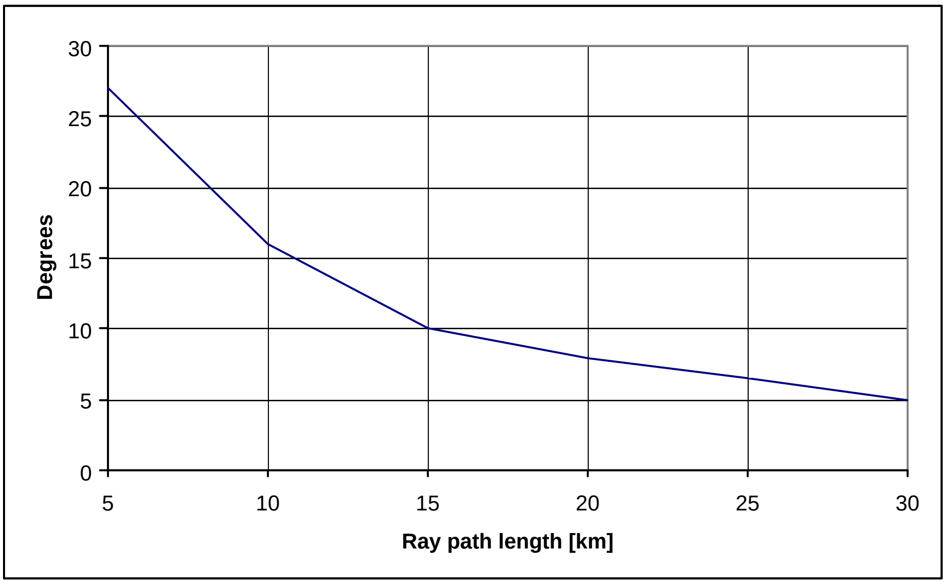

Figure 3.5 Relevant spread in grazing angles as function of length of the traveled energy along a ray.

For rays that have traveled 15 km there are less than 10 dB differences in attenuation between energy that arrives near horizontal and with 10 º grazing angle. Many of the backscattering models, like Essen's model in figure 2.7, show more than 20 dB differences in backscattering strength for many bottom types over the same spread of grazing angles. It is therefore possible that it will be the energy that has experienced multiple reflections from the surface and the bottom and arrives at the higher grazing angles, and shorter distance from the source that will contribute most to the measured backscatter. The same happens for signals that have traveled 30 km along a "ray".

This indicates that it may be difficult to measure the shape of the backscattering curve at low grazing angles to an accuracy needed to determine the bottom parameters. One can argue that using an inversion method, where the sound propagation is modeled, will sort out the problem. However this model introduces other uncertainties related to forward scattering, surface scattering and accurate sound speed measurements that may reduce the accuracy of the estimated bottom parameters from only low grazing angle measurements.

Measurements at the plateau above grazing angles of about 20 degrees may give additional valuable information (see for example figure 2.7) for predicting bottom parameters. These grazing angles are only found at short ranges.

3.2 Short range measurements

As seen above a low frequency active sonar that uses signal designed for detecting submarines at long ranges are incapable of measuring reverberation at the high grazing angles that seems to be needed determining the type of bottom in the area. During the first RUMBLE trial a signal as shown in figure 3.6 was transmitted. It consisted of a short 10 ms long CW pulse followed 5 seconds later by the standard search signal.

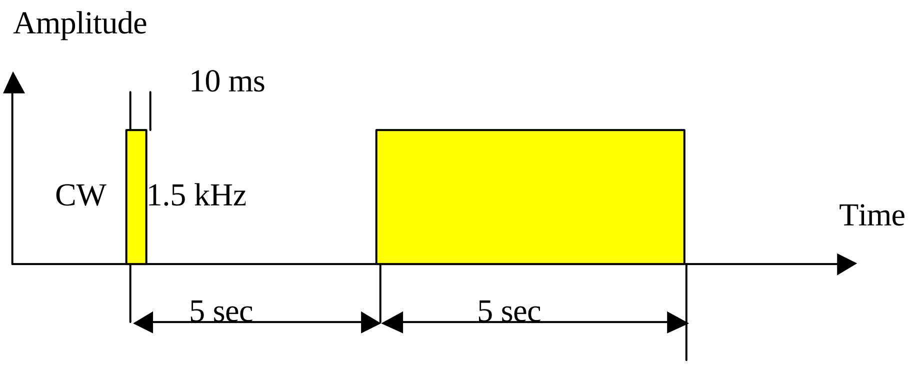

Figure 3.6 Transmitted signal during the first RUMBLE sea trial

The short pulse makes it possible to measure reverberation during the first 5 seconds equivalent to ranges up to 3.7 km in a monostatic case.

3.2.1 Measurements along the receive array

We will here investigate the possibility of doing direct measurements of forward and backscattered energy as function of grazing angles. The results could be used to define some important parameters at high grazing angles that may be used for improving the quality of the parameters found using inversion methods at longer ranges.

Low frequency active towed array sonar systems have physically separated transmitter and receiver arrays. The system used for the RUMBLE experiments has separate towing systems for the transmitter and the receiver. Both are normally placed at the same depth, optimised for detection. Because of very different hydrodynamic properties of the two towing systems the transmitter and receive array will always be at different distances from the towing ship, and for the RUMBLE equipment the difference is about 80 m. In other systems a neutrally buoyant cable attaches the towed array to the transmitter, and a typical transmitter and receiver distance can be about 500 m. It is therefore possible to measure the forward scattering of the signal by a path from transmitter, reflected by the bottom to the receiver. There will of course also be a path reflected from the surface, and if the source and array are placed in the middle of the water column the two signals will arrive simultaneously. In this case we can take the advantage of the capability of the triplet array to discriminate between signals coming from left and right. A small software modification will make it possible to discriminate between signals coming from below and above. The discrimination is better the further from end fire the signals arrive. If the discrimination is sufficient to discriminate between surface and bottom reflections, there is a time gap between the transmitter-bottom-receiver signal and the transmitter-surface-bottom-receiver signal. In this time gap it should be possible to do a direct measurement the bottom reflected signal.

The set up is depicted in figure 3.7. The sound from the source reaches the receiver first by a direct path thereafter the sound reflected from the surface and from the bottom. The distance between the source and receiver is short and therefore it is appropriate in the first instance to ignore sound refraction from variation in sound speed as function of depth.

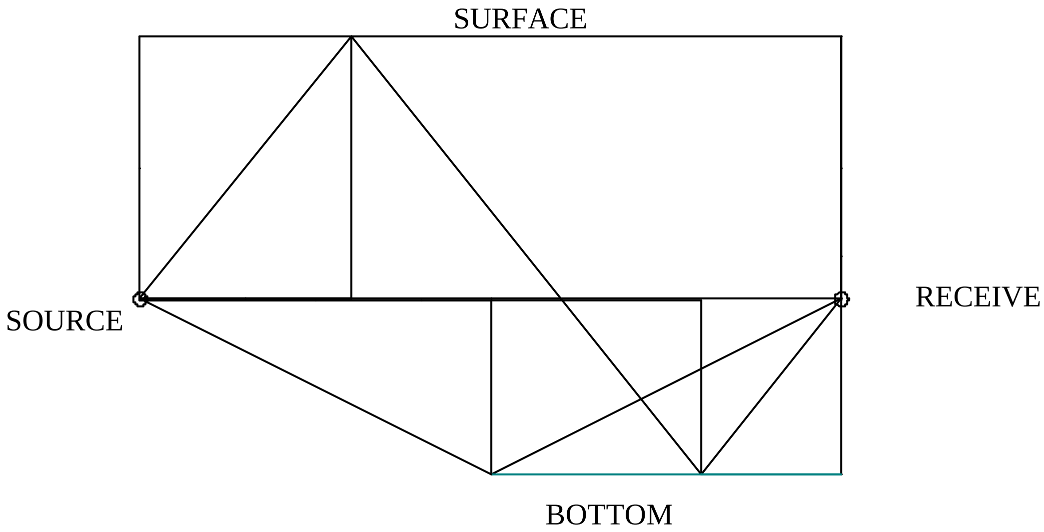

Figure 3.7 Sound paths from source to receiver seen from the side. The sound enters the receiver array from end-fire.

It is then easy to compute the propagation time for the signals: source-bottom-receiver and source-surface-bottom-receiver. The result is shown in figure 3.8 for the measurement set-up used in the first RUMBLE trial. Source and receiver at 50 m depth and source receiver distance about 80 m.

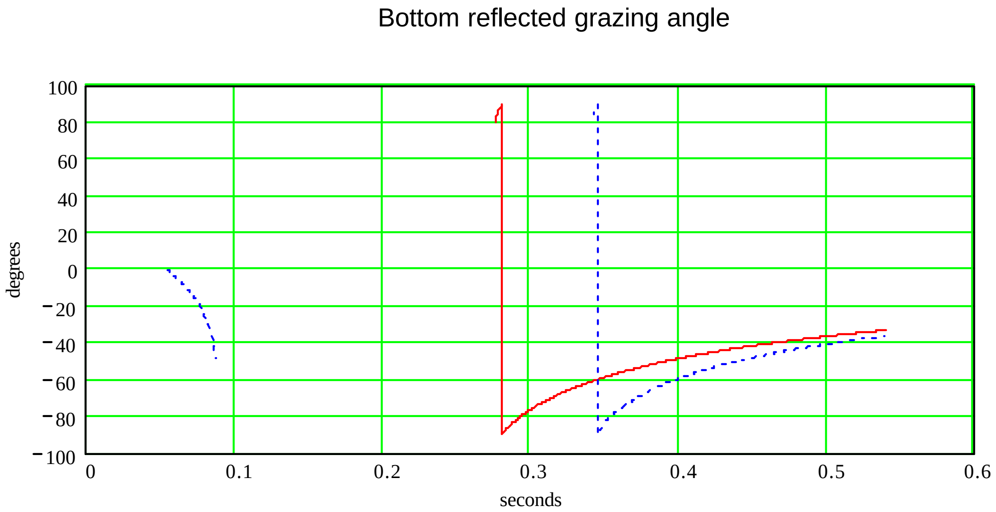

Figure 3.8 Grazing angles of bottom reflections as function of time.
Source and receiver at 50 m depth, source receiver distance 80 m, water depth 250 m.
Red solid curve: source-bottom-receiver path. Dotted blue curve: source-surface-bottom-receiver path

It is seen that there is only a small window of about 70 ms between the two arrivals. In this small time window the bottom reflected signal is first reflected at about 80 degrees and moves along the bottom until it is reflected vertically up to the array at 90 degrees. Thereafter the signal is scattered back to the array and the angle reduces to about 60 degrees before the surface-bottom reflected signal arrives close to 90 degrees to the array. Accordingly only signals reflected and scattered near the vertical can be measured with this set up, and reflections at these angles are not interesting RUMBLE data.

The case would be very different if the sonar could be towed deeper, as shown in figure 3.9.

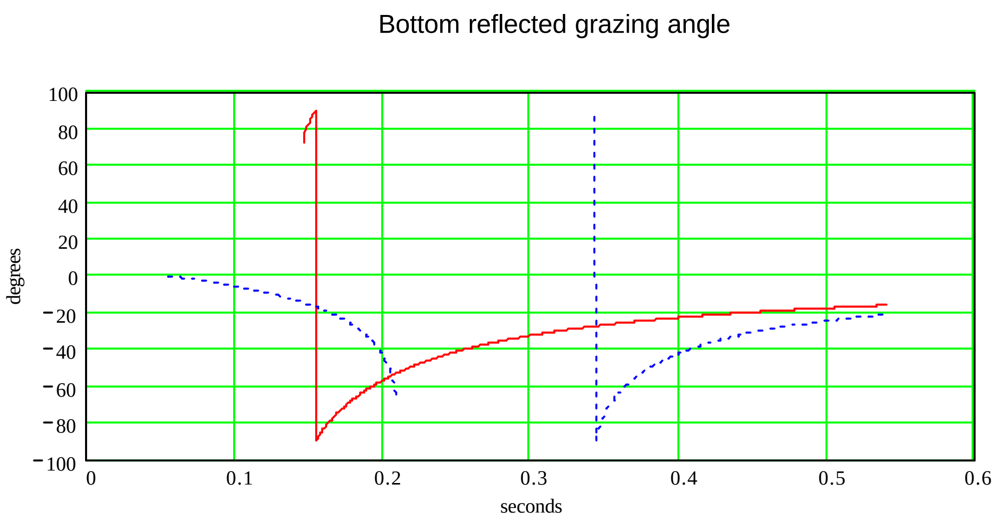

Figure 3.9 Grazing angles of bottom reflections as function of time.
Source and receiver at 150 m depth, source receiver distance 80 m, water depth 250 m.
Red solid curve: source-bottom-receiver path. Dotted blue curve : source-surface-bottom-receiver path.

In this case it would be possible to follow the angle from the bottom reflection all the way until it is scattered at about 25 degrees from horizontal. Unfortunately this configuration is not possible with the sonar used in the RUMBLE experiment. It therefore seems unlikely that a direct measurement of backscattering strength according to this method is possible for the RUMBLE experiment.

3.2.2 Measurements at short range and calm surface

After the first reflected signal has arrived at the array, the bistatic-backscattered signals will start to arrive, progressively more towards broad side as ranges increase, as shown in figure 3.10.

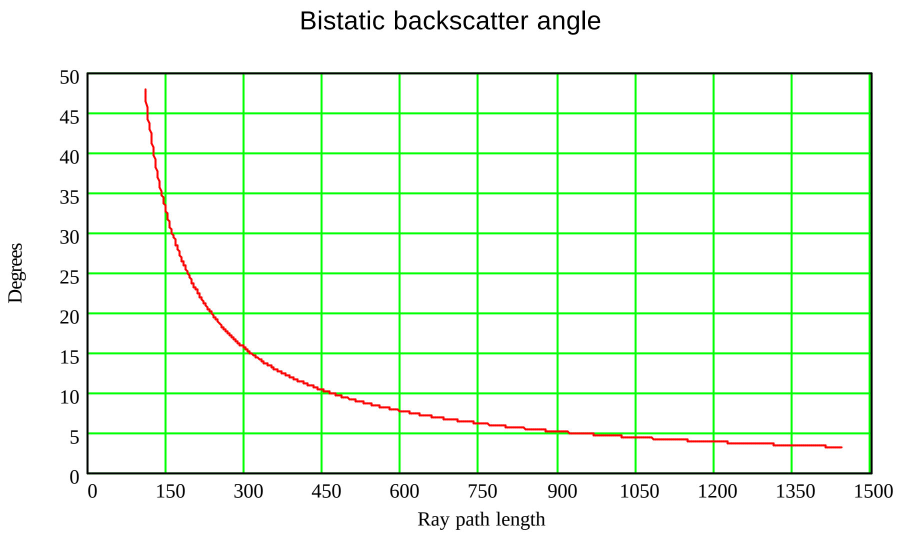

Figure 3.10 Bistatic backscatter angle as function of slant range in meters from transmitter to the bottom. Source and receiver at 50 m depth, source receiver distance 80 m, water depth 250 m.

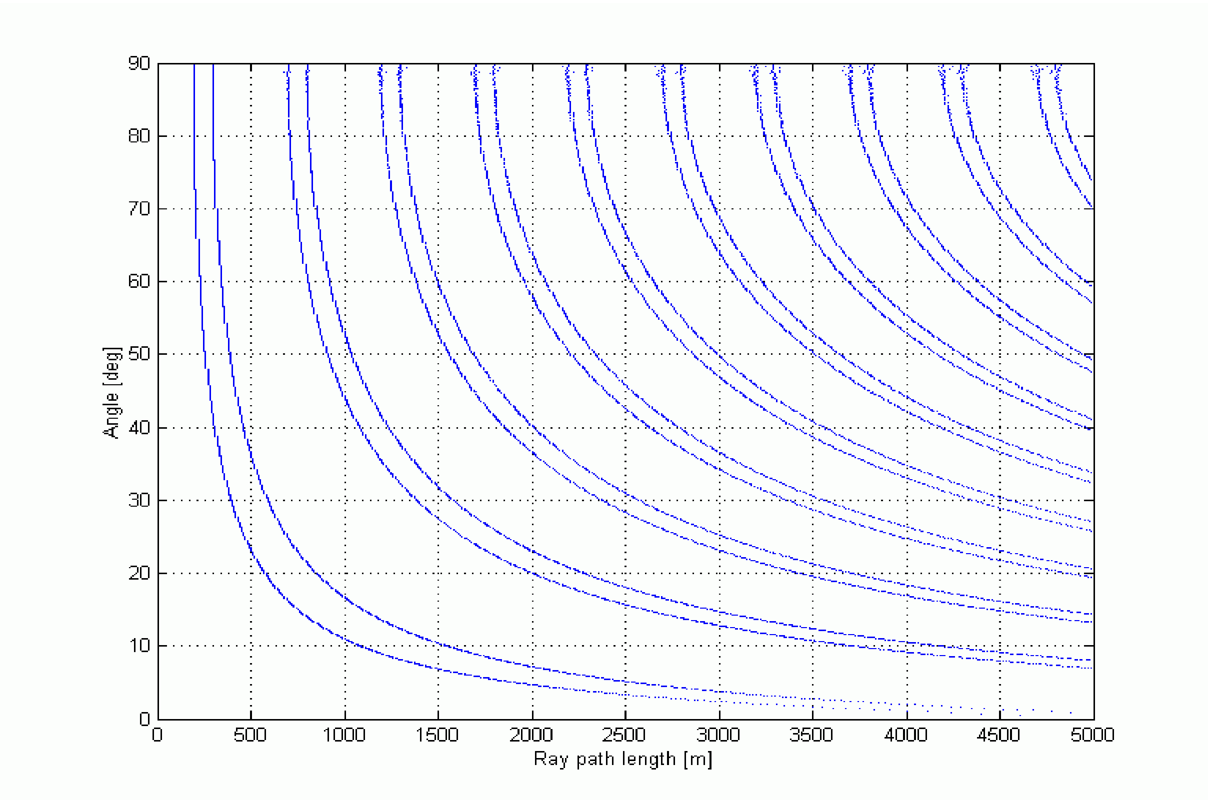

Figure 3.11 Grazing angle at the bottom as function of traveled distance, the first 5000 m, no wind.

According to the “relevant measurements” defined in section 2.7, backscatter angles from about 50 degrees down to 5 degrees are of interest. Backscatter at 50 degrees occurs 180 ms from transmission, equivalent to a path length of 270 m, and arrives at a hydrophone 80 m from the source at an angle to the array of approximately 20 degrees off broadside.

Backscattered energy arriving from more than 1000 m from the array has bistatic angle less than 5 degrees off broadside and can probably be considered as monostatic. When the short signal has traveled 1000 m, there are four sets of short pulses arriving at the bottom as shown in figure 3.11. Furthest away from the source the direct signal from the source hits the bottom. A little closer to the source the surface reflected signal arrives at the bottom. At the same time closer to the source the source-bottom-surface reflected path with grazing angle 42 degrees arrives, and even closer the source-surface-bottom-surface reflected path arrives with a grazing angle of 50 degrees. Since these signals arrive simultaneously, it will only be possible to separate them by using a receiver with narrow vertical beams. If however the signals have significant difference in energy it could be possible to determine the important arrivals. The energy of the different arrivals is shown in figure 3.12.

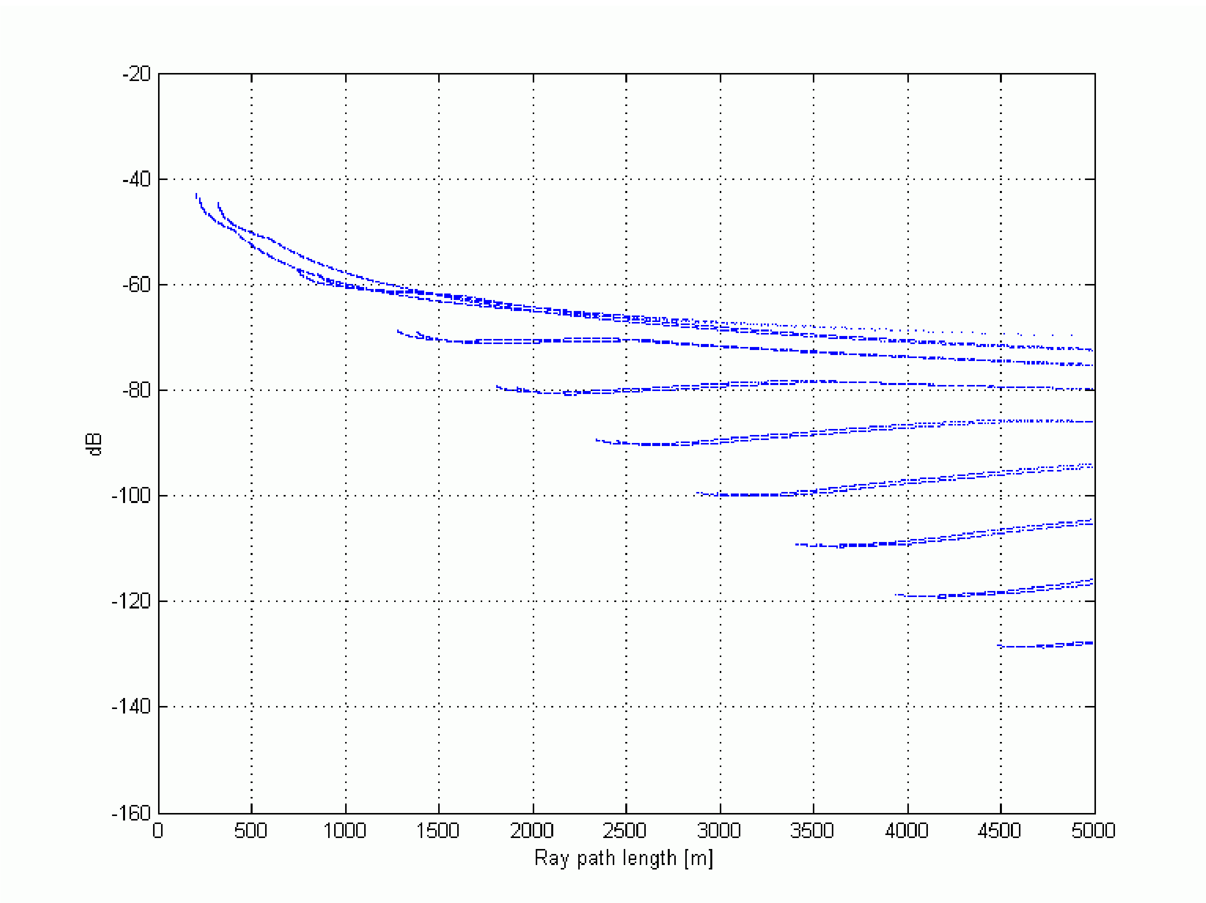

Figure 3.12 Attenuation of the different arrivals as function of ray path length, no wind.

At ranges less than about 700 m the direct and first surface reflected ray-bundle arrives alone. In this time period it seems possible to measure backscatter coefficients from grazing angle of close to 90º to about 30º.

At longer ranges many of the paths produce similar energy at the bottom, and since the bottom backscattering curves increase fast with grazing angle for low grazing angles, the signals arriving with high grazing angle will dominate the backscattered energy, making it difficult or impossible to measure backscattered energy from signals arriving at the bottom with low grazing angles.

Inversion methods must be used for estimating backscattered energy for low grazing angles even at short-range measurements.

3.2.3 Effect of wind

Wind will spread the scattering angle from the surface. At even moderate windy conditions, 5.14 m/s equivalent to Sea State 2, the result is a much more complicated and disturbed sound field at longer ranges, as shown in figure 3.13.

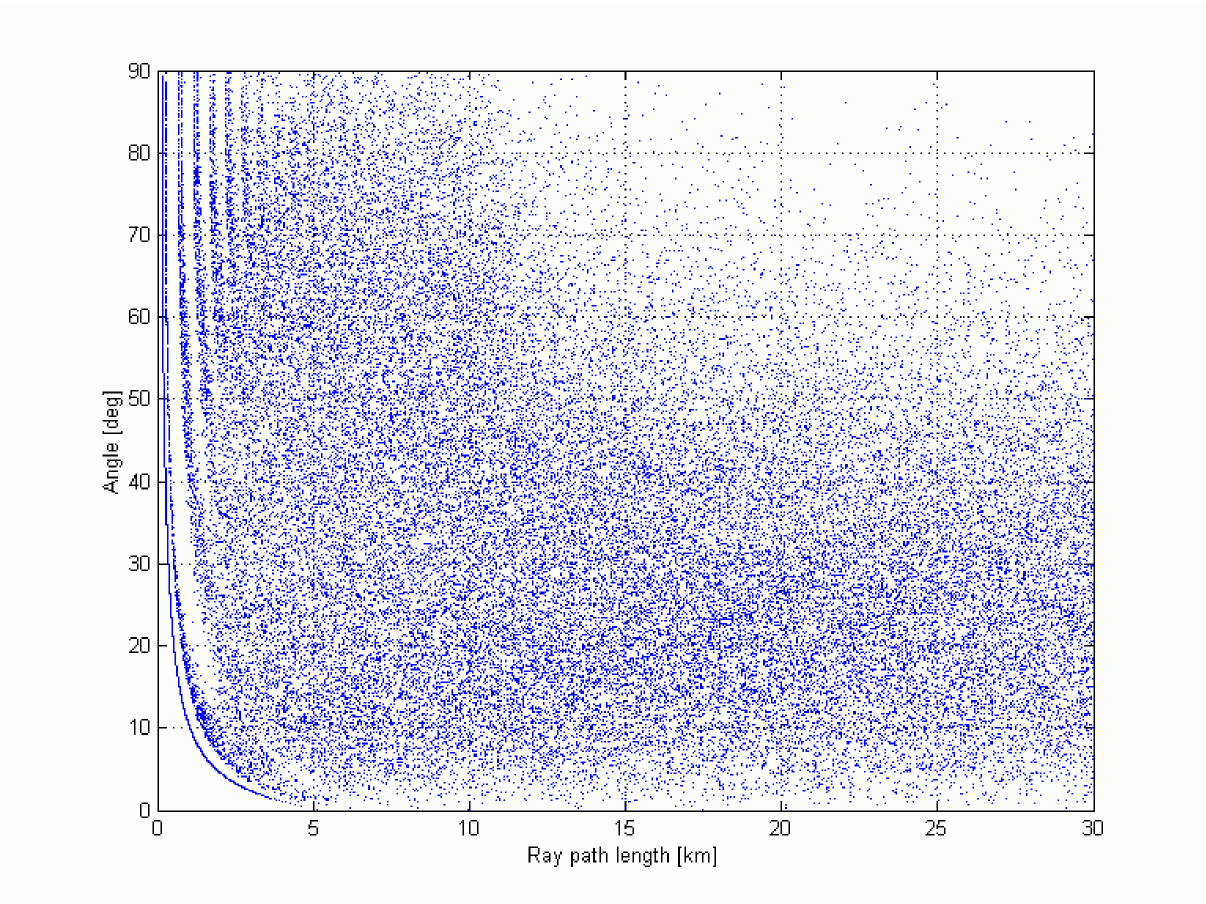

Figure 3.13 Grazing angle at the bottom as function of traveled distance. Wind speed 5.14 m/s.

This is the same case as in figure 3.3, except that the wind is increased from 0 to 5.14 m/s. Even at short ranges the ray-bundles have disappeared and the grazing angles are distributed randomly over a wide window of angles. At short ranges there is more structure as shown in figure 3.14.

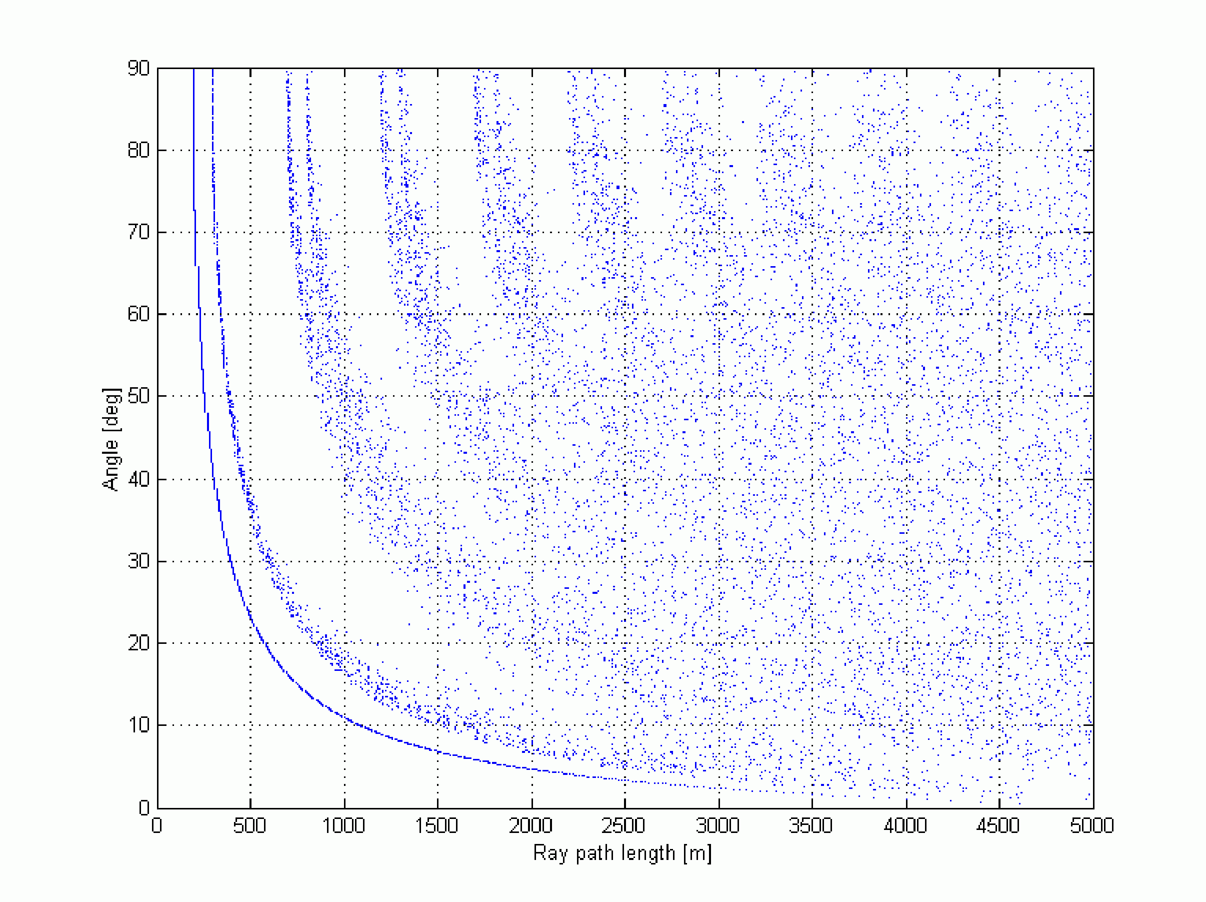

Figure 3.14 Grazing angle at the bottom as function of traveled distance for the first 5000, wind speed 5.14 m/s equivalent to Sea State 2.

Figure 3.14 indicates that there is a possibility to get relevant data from short-range measurements. The intensity of the energy arriving at different grazing angles is shown in figure 3.15.

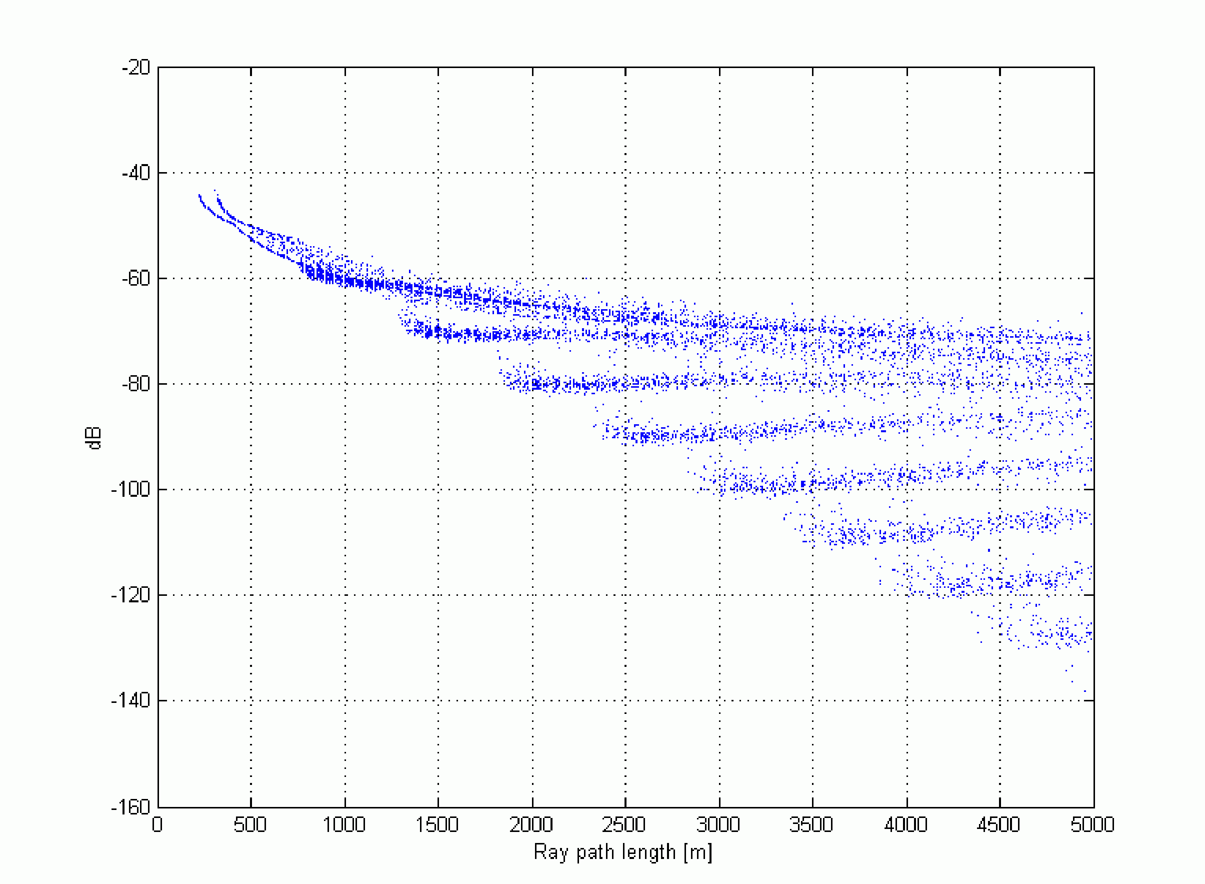

Figure 3.15 Attenuation of the different arrivals as function of ray path length, wind speed 5.14 m/s.

It is seen that the direct path is strong and more stable than the surface reflected paths at short ranges, indicating that by averaging several consecutive pings it should be possible to get estimation of backscattering strength at least for ray paths up to 700 m and possible out to about 2000 to 3000 m. This would cover the necessary spread of grazing angles needed for determining the relevant backscattering function, and from it the type of bottom if the backscattering function follows one of the physical models.

These crude simulations seem to indicate that reasonably good long-range data can only be expected when the sea is calm since generally all energy at long ranges has been reflected several times from the surface. As the sea surface gets rougher, short-range measurements seem to provide an alternative. The diffusive spread of the energy from the surface may in fact make it easier to determine the backscattered energy at low grazing angles. The fluctuation of the surface reflected signals would increase with the number of surface reflections. Signal paths with few surface reflections would be more stable. By proper ping-to-ping processing the backscattered energy from the few stable paths may be found.

3.3 A special case, unfavourable oceanographic conditions

So far we have used a typical sound speed profile for May/June in Vestfjorden. In October the sound speed profile can be very different, as shown in figure 3.13. When the sonar system is towed shallow, at about 50 m, sound is refracted upwards above the source and downwards below the source, as shown on the ray trace plot in figure 3.14 The result is that no energy arrives at grazing angles lower than about 6 degrees at any range, as shown in figure 3.15.

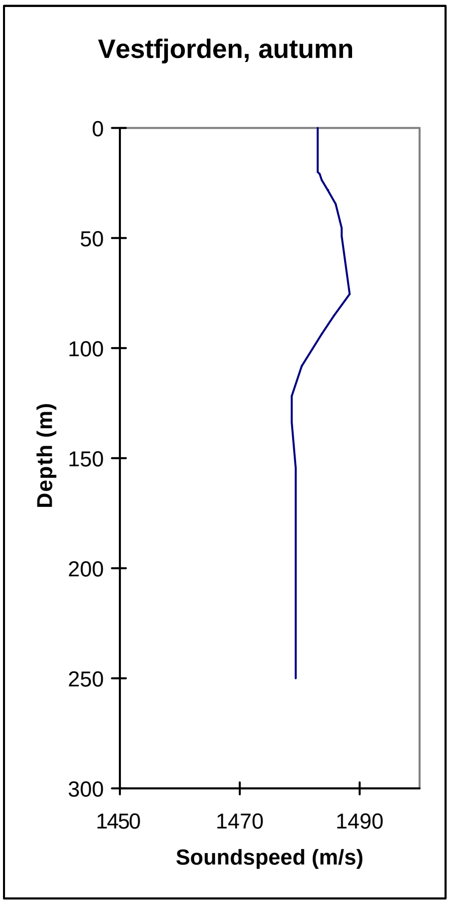

Figure 3.13 Sound speed profile for Vestfjorden in October.

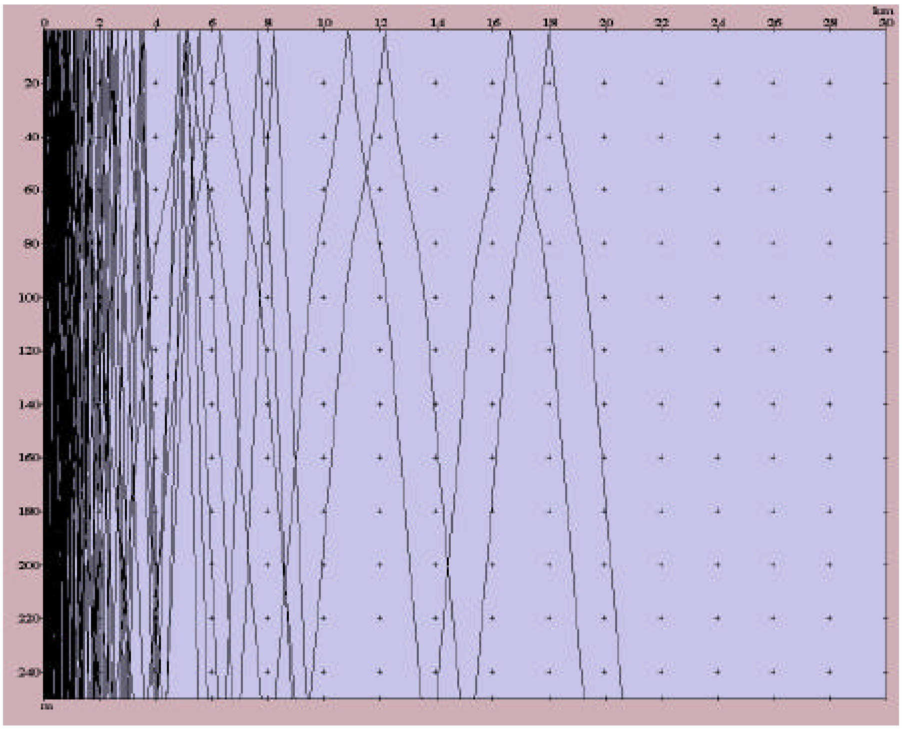

Figure 3.14 Ray trace showing four surface and three bottom reflections.

If the source and receiver were towed at another depth it would be possible to avoid the strong downward refraction so that energy at low grazing angles would be present at the bottom like in the previous case. It is therefore important that the towing depth is chosen according to the sound speed profile for gathering the information needed for estimating bottom reverberation parameters.

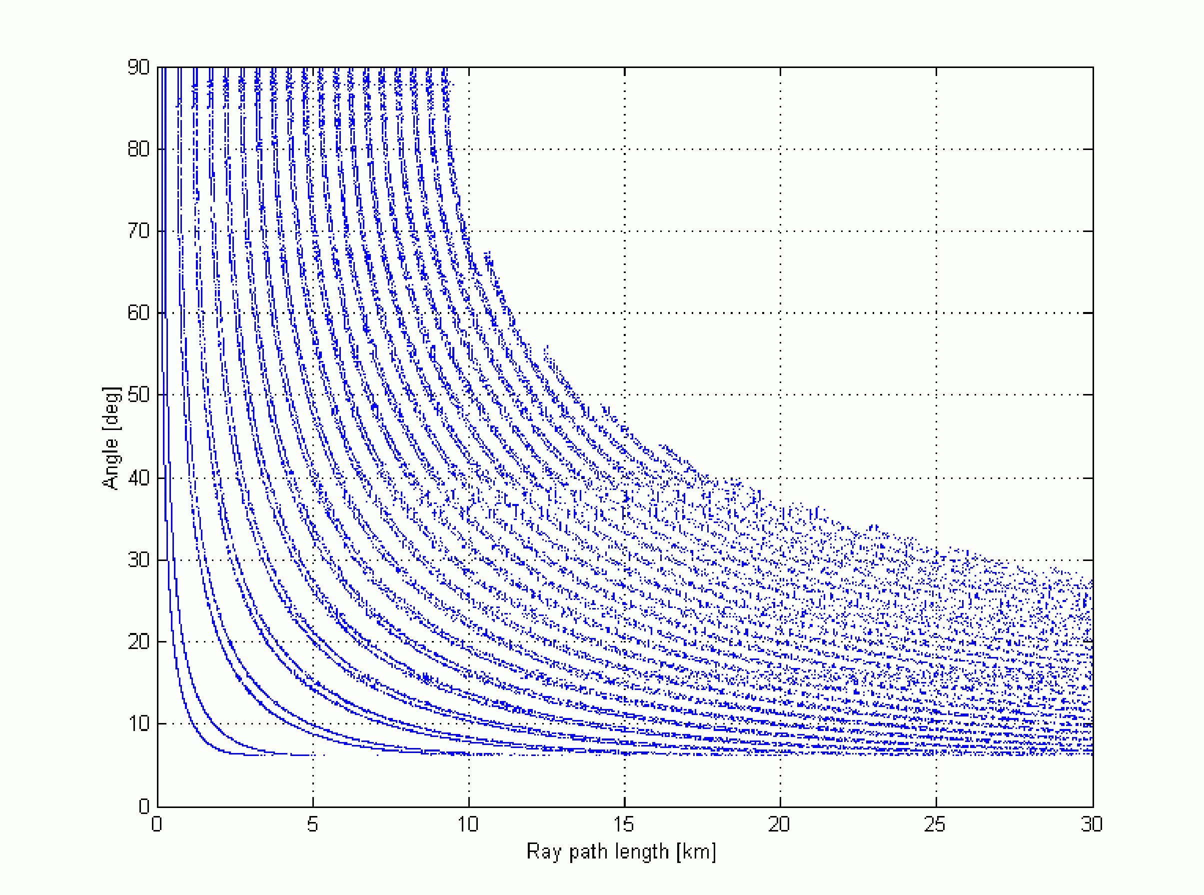

Figure 3.15 Grazing angle at the bottom as function of traveled distance. Source and receiver depth is about 50 m.

4 CONCLUSION

In order to establish the backscattering function and associated bottom parameters that may be the cause of reverberation in the area during different oceanographic conditions it seems necessary to measure backscattering levels at grazing angles from close to zero to may be as high as 50 to 60 degrees. It is not necessary to sample this range of grazing angles in small steps. A few sample values covering the 0 to about 60 degrees range seems adequate.

To cover this range both short and long-range measurements must be made. The assumption that the bottom is similar at short and long-range measurements is necessary for combining these different measurements into one result.

Measurements along the array have the possibility of measuring forward and backscattered energy from "clean" ray paths if the distance between source and receiver is sufficiently large. This is not the case for the sonar system used for the RUMBLE trial, since the source and receiver are individually towed critical angle systems.

A Low Frequency Active system with a sufficiently long neutrally buoyant cable connecting the towed array to the source may have sufficient separation for this method to function. This seems to be the case for systems being delivered to the New Norwegian Frigates.

In rough weather it seems that it will be difficult to measure bottom backscattering accurately at long ranges.

At short range, however, the diffusive spread of energy from the surface may be used to an advantage. By proper filtering and ping-to-ping integration it may be possible to separate the source-bottom path from the paths reflected from the surface. It may even be possible to measure backscattering at lower grazing angles than when the sea surface is flat.

The transmitted signal should therefore consist of short pulses for short range measurements, followed some time later by the signal used for detecting submarines, which also can be used for long range inversion. In the first experiment one 10 ms CW pulse was transmitted 5 seconds before the ASW pulse. There is, however, enough bandwidth and time available to transmit one 10 ms CW pulse at the lower part of the frequency band followed by one similar pulse at the higher end of the frequency band, and possibly one in the centre of the 1 kHz frequency band. Each pulse has a bandwidth of about 100 Hz, and even with only a limited amount of amplitude shading the signal can easily be separated by simple bandpass filters in the receiver chain.

Measurements from the first sea trial indicate that the energy in the short CW pulse may be too low for measuring reverberation at the end of the 5-second period before the long ASW pulse is transmitted. The possibility to transmit a short “ASW” pulse about 100 ms long, with the same range resolution as the ASW signal should be investigated. This pulse should be transmitted about 5 seconds after the series of short CW pulses, to enable the reverberation to decay below background noise. About 20 seconds later the ASW pulse would be transmitted. In this way the reverberation can be measured at all ranges without any gaps.

It is very important that no saturation effects take place during short-range measurements. The levels of the short CW and “ASW” pulses should therefore be controlled during the trial.

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