FFI/849/914

Sonar Simulation for the Action Speed Tactical Trainer at KNM Tordenskjold

Karl Thomas Hjelmervik, Amund Lorentz Gjersøe
and Svein Alsterberg

FFI-rapport 2007/02348

FORSVARETS FORSKNINGSINSTITUTT
Norwegian Defence Research Establishment
P O Box 25, NO-2027 Kjeller, Norway

FORSVARETS FORSKNINGSINSTITUTT (FFI)
Norwegian Defence Research Establishment

P O BOX 25
N0-2027 KJELLER, NORWAY

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE
(when data entered)

REPORT DOCUMENTATION PAGE

1) PUBL/REPORT NUMBER FFI/RAPPORT-2007/02348	**2) SECURITY CLASSIFICATION** UNCLASSIFIED	**3) NUMBER OF PAGES** 39
1a) PROJECT REFERENCE FFI/849/914	**2a) DECLASSIFICATION/DOWNGRADING SCHEDULE** -	

4) TITLE
Sonar Simulation for the Action Speed Tactical Trainer at KNM Tordenskjold

5) NAMES OF AUTHOR(S) IN FULL (surname first)
HJELMERVIK Karl Thomas, GJERSØE Amund Lorentz, ALSTERBERG Svein

6) DISTRIBUTION STATEMENT
Approved for public release. Distribution unlimited. (Offentlig tilgjengelig)

7) INDEXING TERMS

	IN ENGLISH:	IN NORWEGIAN:
a)	Training	Trening
b)	Sonar	Sonar
c)	Anti-submarine	Anti-ubåt
d)	Acoustic modelling	Akustisk modellering
e)	Ray trace	Strålegang

THESAURUS REFERENCE:

8) ABSTRACT

This report describes a sonar simulation module planned implemented into Kongsberg Defence and Aerospace’s Action Speed Tactical Trainer. A land-based and modular training facility for frigate crew members. The sonar simulation module generates sonar audio, echoes and tracks based on an acoustic propagation model called Lybin. Lybin is the property of the Norwegian Navy.

The acoustic modelling includes depth-dependent sound speed profiles, high-resolution topography and varying sonar settings. Both real targets and terrain features generate echoes. Methods of running the model in real-time are proposed.

9) DATE	**AUTHORIZED BY** This page only	**POSITION**
2008-02-15	John-Mikal Størdal	Director of Research

ISBN 978-82-464-1348-8

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE
(when data entered)

EXCECUTIVE SUMMARY

The Norwegian Navy is procuring five modern frigates with helicopters. Anti-submarine warfare (ASW) in littoral waters is particularly demanding, - the Fridtjof Nansen-class sonar systems are high-end systems suitable for littoral waters.

The Fridtjof Nansen-class frigates are equipped with two different sonars; a hull-mounted sonar and a towed array. In addition the helicopter will have installed a FLASH dipping sonar. The newly acquired sonar systems are highly advanced and support a large number of sonar setting combinations. The increasing complexity of the sonar systems demands more and improved training of the sonar operators and their supervisors. Simultaneously, a higher pressure on Navy budgets requires cheaper alternatives. This report presents a realistic, land-based sonar simulation module using the Navys own acoustic model Lybin. The module is suggested implemented in the all ready existing Action Speed Tactical Trainer (ASTT) at the Navy base in Haakonsvern. By increasing the realism of the ASTT an element of skill-based training is added to the tactical trainer. This will raise the skill level of sonar operators before they are stationed at the Fridtjof Nansen-class frigates.

The sonar simulation module includes sonar data at several levels. It estimates sonar audio along the listening beam. It simulates echoes and tracks both from terrain and targets. The sonar operators may therefore learn how to cope with the difficult sonar conditions inside Norwegian fjords or in littoral waters before getting on the frigate. This includes what pulse types are most effective in different circumstances and for different targets, and what tilt angle should be used for different sound speed profiles.

The Oslo-class Spherion sonar is used in the examples, but the method can easily be extended to the new sonar systems on the Fridtjof Nansen-class frigates.

CONTENTS

Sonar Simulation for the Action Speed Tactical Trainer at KNM Tordenskjold

1 INTRODUCTION

FFI project SIMSON has developed a model for numerically generating sonar tracks and audio in real time, based on realistic environmental data and submarine and surface target activity. This model is henceforth called the sonar simulation module. It is a proposed improvement of the existing sonar simulation software in the Action Speed Tactical Trainer (ASTT) at KNM Tordenskjold provided by KDA Simulation & Training. The intent is to include a potential for skill-based training in addition to the present tactical training potential.

The model runs LYBIN[1] to predict target signal excess and also omni directional reverberation and noise. The results are used to model audio along a beam and also target and false alarms in all directions. Target echoes are due to surface and sub-surface vessels, defined by the instructor. False alarms are mainly caused by bathymetric features or acoustic convergence zones on the surface. Echoes from schools of fish or marine mammals are not taken into account.

A paper was written on the presented method for the Underwater Defence Technology Conference and Exhibition in Hamburg in 2006, ref (1).

This work was finished in 2006, and the proposed simulator has been implemented into the Action Speed Tactical Trainer at Haakonsvern by Kongsberg Defence & Aerospace.

Chapter 2 gives a short description of Lybin. Chapter 3 presents a method of extracting audio data from modelled reverberation. Chapter 4 describes a method of generating echoes from modelled reverberation data. Chapter 5 presents a simple tracking-algorithm used in the sonar simulator module. Chapter 6 describes the output of the sonar simulation module. Finally the conclusion is given in chapter 7.

2 ACOUSTIC MODELLING AND LYBIN

An acoustic propagation model is needed to predict propagation of sound in the training environment. The model must be able to predict transmission loss and reverberation. Refer to (5) for definitions of reverberation and transmission loss. High resolution modelled reverberation data is needed to compute the audio for the operator, see chapter 3. In addition

---

[1] LYBIN is the property of Norwegian Defence Logistic Organization NDLO/Sea. It is an acoustic ray trace model.

omni directional, modelled reverberation is needed to compute an echo cloud[2] surrounding the sonar.

The acoustical raytrace model Lybin was chosen both for its ability to predict transmission loss and reverberation, and also since it is the property of the Royal Norwegian Navy. However, Lybin is not a three dimensional model. Lybin computes the transmission loss and reverberation in a single vertical cross section. It uses a bottom profile and other environmental data from that cross section. Refer to (2) and (6) for more information on Lybin input parameters. Lybin must therefore be run in *n* directions to model the omni-directional reverberation. Due to extensive work by Svein Alsterberg and Elin Dombestein at FFI, Lybin has been optimised for speed and prepared for batch processing[3], ref (3), both of which are very important when determining the echo locations. The use of Lybin in project SIMSON is briefly described in Elling Tveit et al in ref (2), and the need for simulators in Wegge et al, ref (8).

Since the methods described in the following chapters all utilizes Lybin-modelled reverberation, an example of bottom reverberation is presented in Figure 2.1.

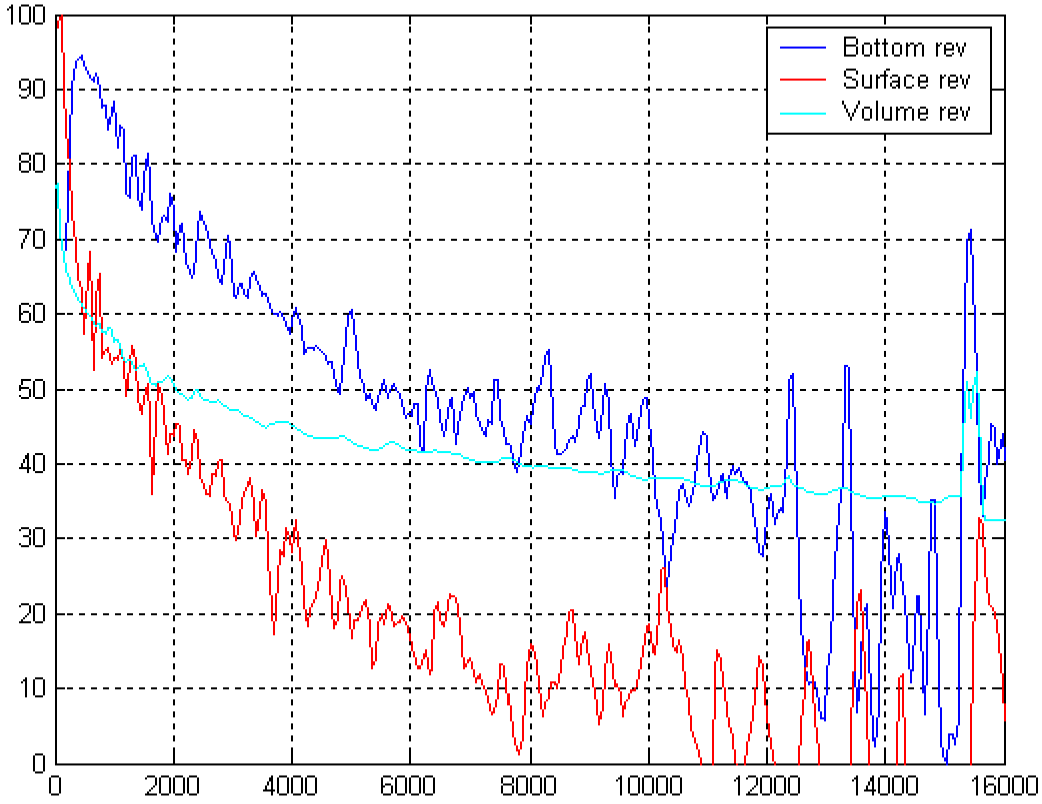


Figure 2.1 Lybin modelled bottom, surface and volume reverberation.

---

[2] An echo cloud is defined as all echoes generated from a single sonar transmission in all beams. An echo is a reflected replica of the initial transmission, regardless of the type of reflector.

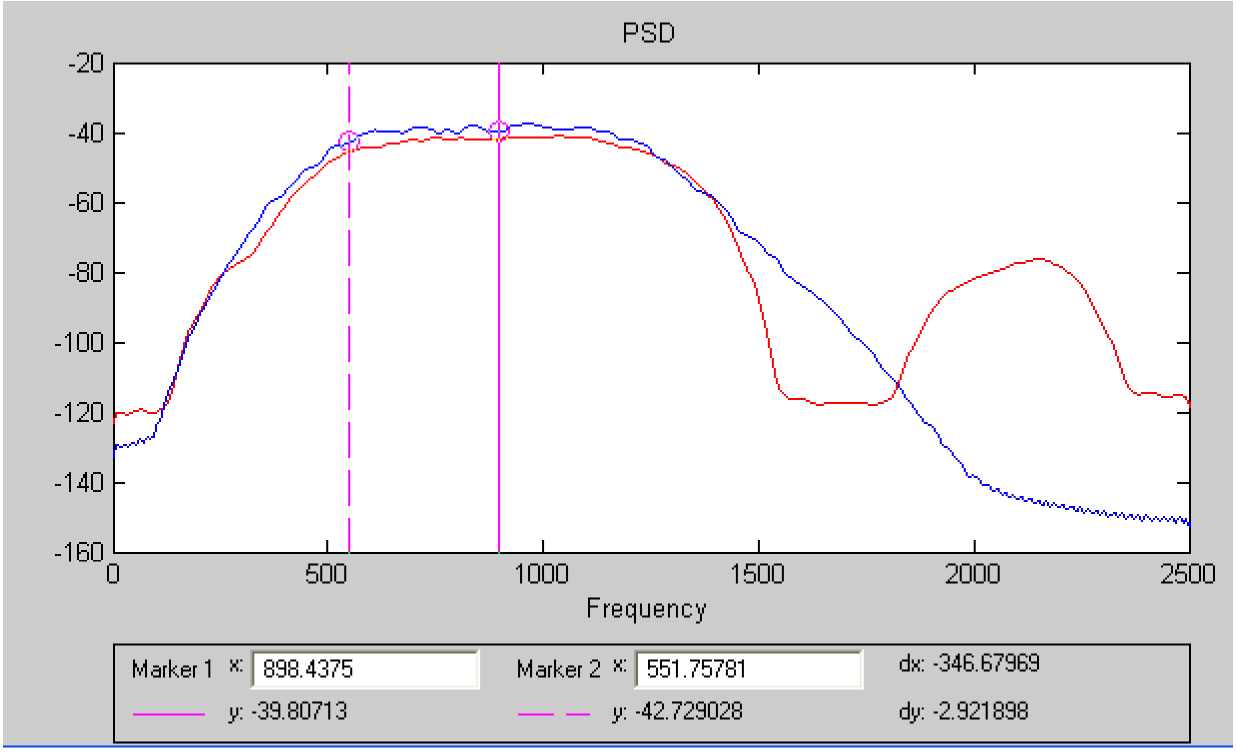
[3] Batch processing is the method of running a program in loops changing one or more parameter for each iteration.

3 SONAR AUDIO GENERATION

The audio signal of a sonar system is based on target echoes, reverberations and noise. The approach described in this chapter focus on the background-noise and the reverberation. When working with sound, the word *feel* must be used. The sound is not necessarily perfect to the ear, even though the sound is theoretically right. In the work described here the *feel* will guide us to realistic sound.

3.1 The sound of background-noise

To gain realistic sonar audio one has to get the right background-noise. The sonar systems on the Oslo-class frigates include some digital modulators that narrow the frequency band of the audio. The audio has a centre frequency at 900Hz, and a 600Hz bandwidth. The spectrum characteristics for the real audio are as the red line displays in Figure 3.1.



Marker 1 x: 898.4375 y: -39.80713

Marker 2 x: 551.75781 y: -42.729028

dx: -346.67969

dy: -2.921898

Figure 3.1 Spectrum characteristics of the sonar audio. The red line is the real system's audio, and the blue line is the simulated background-noise spectrum.

The background-noise must be filtered to gain the same characteristics as real audio. This is done by combining a 8th order Butterworth low-pass filter with a cut-off frequency at 1200 Hz, and a 4th order Butterworth high-pass filter with a cut-off frequency at 585 Hz. The resulting audio has the characteristics as displayed by the blue line in Figure 3.1. The real and the generated audio have similar characteristics within the range of -3dB of the centre frequency gain.

The amounts of background-noise depend on parameters like audio direction, ship's speed and self-noise, sea state and nearby traffic. In our case we focus solely on altering the background-noise based on sea state.

The sea state as a parameter affects the amount of background-noise relative to reverberation and target echoes. It also influences the periodic variation of the background-noise's strength. This means that the intensity of the background-noise will fluctuate. By doing so, the realism of the audio is maintained. The human ear will recognise static coloured noise as something unnatural, but by having fluctuating noise we mean that this will give the sound a more natural impression.

The fluctuation is made by the function described in Equation 1.

$$\mathrm{Gain}(i) = \frac{\sin(f \cdot i \cdot \pi \cdot 2/f_s) + \sin(f/2 \cdot i \cdot \pi \cdot 2/f_s)}{2*(1-\alpha)} + \alpha \qquad \text{Equation 1}$$

Where:

i: iterator
f: frequency based on the current sea state
f_s: sampling frequency
(α-1): percentage fluctuation of the noise

Equation 1 will produce a gain signal that will be used as a gain control on the background-noise. Figure 3.2 displays an example of the gain control applied on a signal of random noise.

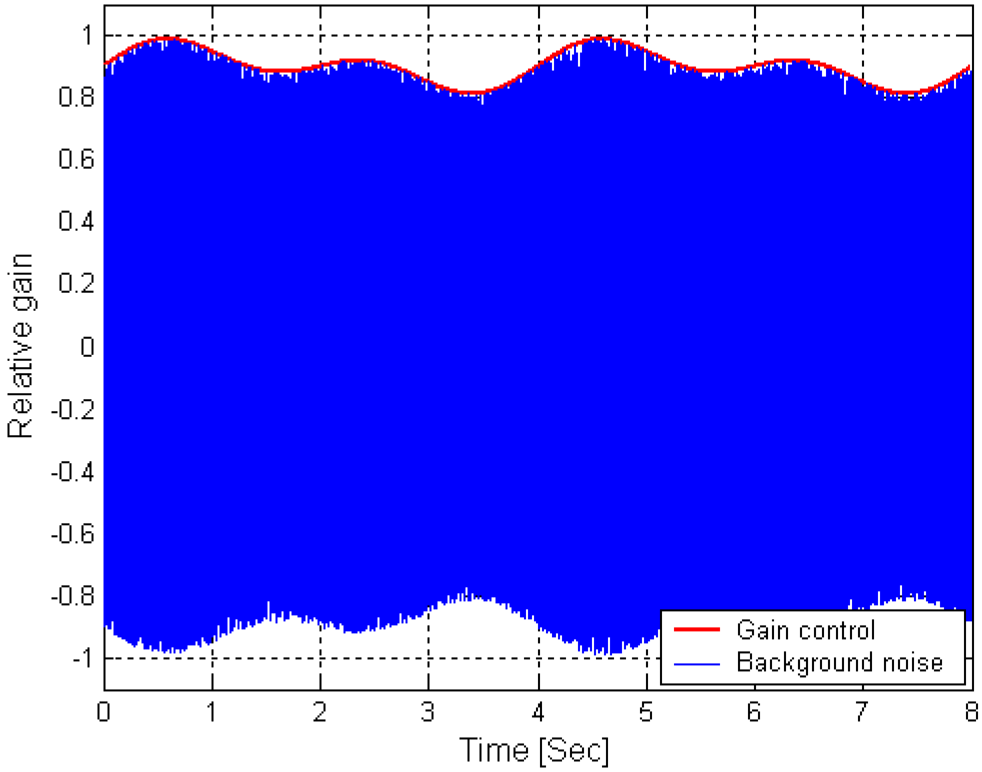


Figure 3.2 The result of applying the gain signal from Equation 1 on to a random noise example. The parameters were f: 0.5Hz, α: 90% and f_s*: 8000Hz*

The parameters *f* and *α* must be set in a look-up table based on the sea state as search parameter.

3.2 The sound of reverberation

The reverberation is computed by Lybin. The results from Lybin are treated differently depending on the transmission mode of the sonar, e g CW-mode and FM-mode.

3.2.1 The sound of reverberation in FM-mode

The results from Lybin will contain peaks where there are predicted to be reverberation. The peaks also define the strength of the reverberation. By finding all of the peaks in the Lybin -result and convert metres to time, we get the places to put reverberation in the audio signal. The peaks are also used to scale the intensity of the sound. Some peaks will have strengths below the suspected noise, and those peaks are left out.

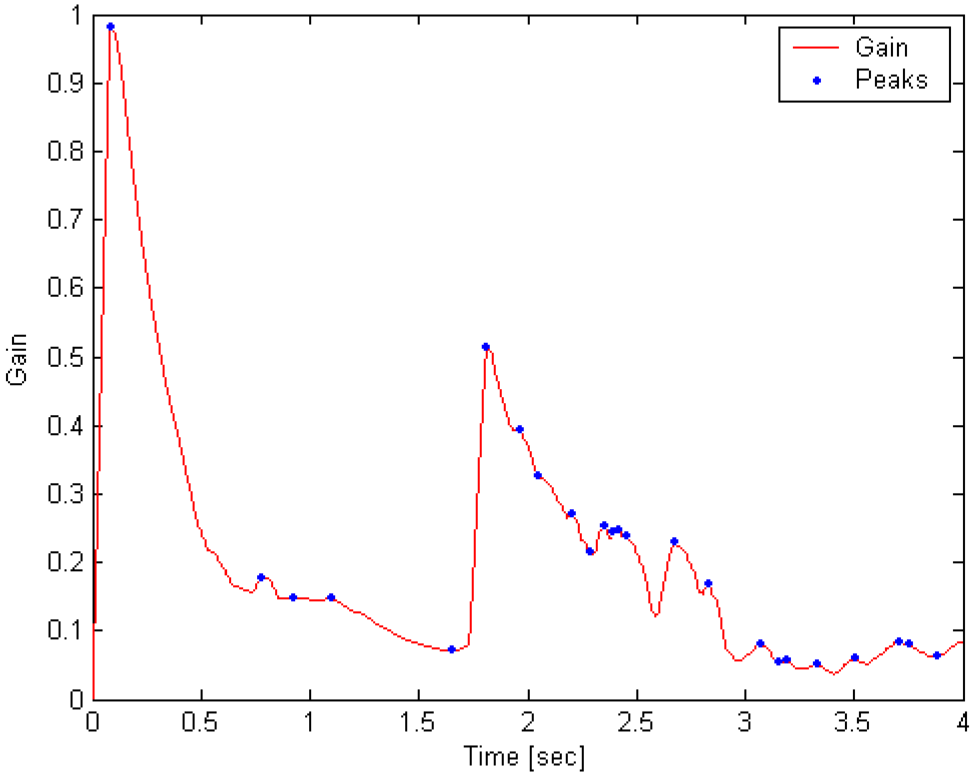


Figure 3.3 For sonar audio in FM-mode the reverberation is based on the peaks (blue dots) of the LYBIN-result (red line). Peaks that are lower than the suspected noise are left out of the audio signal.

When applying the transmitted pulse on all the peaks, some will overlap. But this is a natural effect often heard in real sonar audio.

The resulting audio signal is displayed in Figure 3.4. The overlapping parts, especially around 2.5 sec, lead to an increase of the intensity of the reverberation, and thus the ragged envelope around that area.

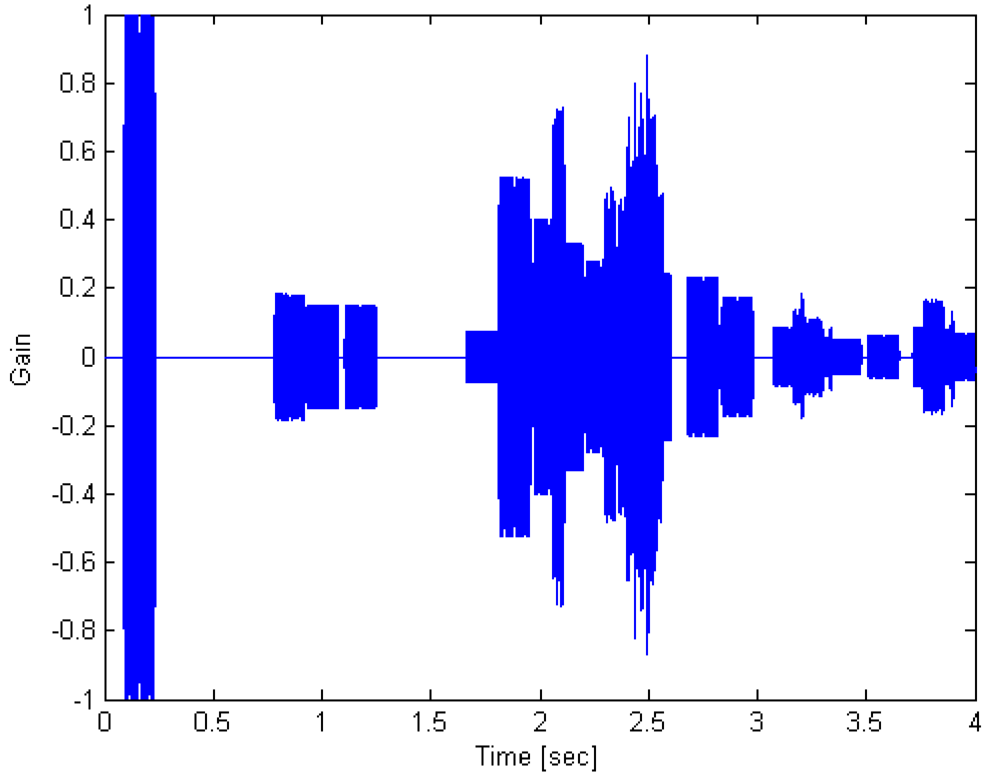


Figure 3.4 The reverberation audio signal based on the peaks in Figure 3.3

3.2.2 The sound of reverberation in CW-mode

In CW-mode we use a slight different approach. The Lybin-result is smoothed and used directly as a gain control signal to a continuous tone. At some level the reverberation is weaker than the background-noise, so for these cases the gain is set to zero.

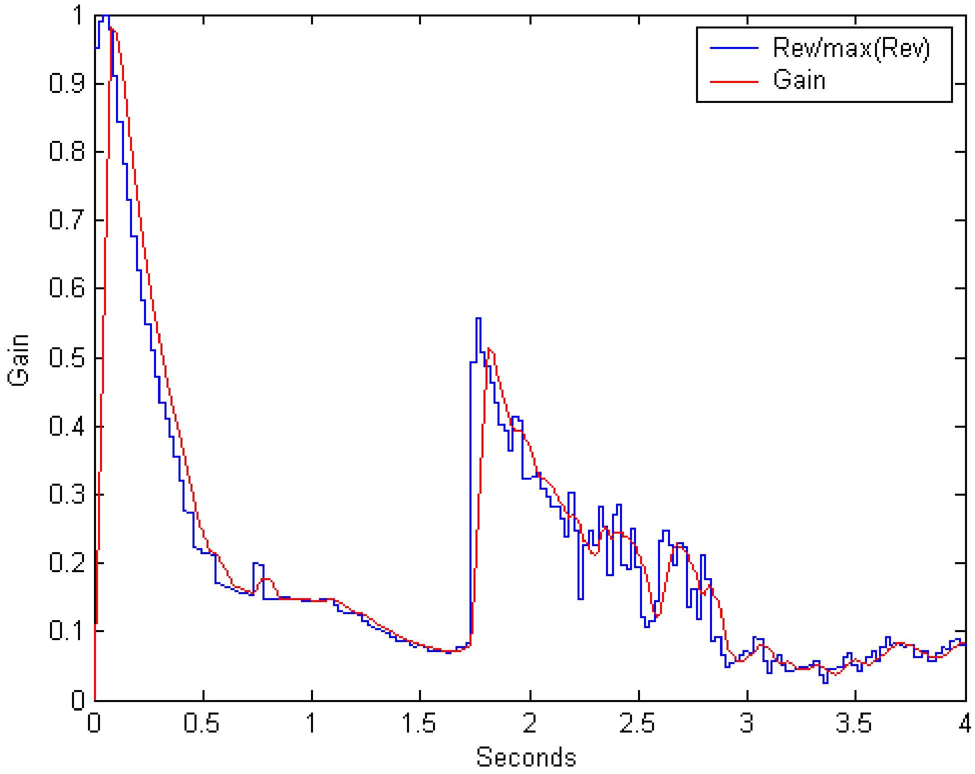


Figure 3.5 Lybin-result (blue line) that has been smoothened (red line). The smoothened signal is used as a gain control signal when making reverberation in CW-mode.

The modelled reverberation is smoothed to make the variation in intensity less rapid. At 1.75 sec in Figure 3.5 the Lybin-results show a strong reverberating area. The blue line is quite steep. If used directly as a gain control, the sound will increase too rapidly in intensity. The *feel* of the reverberation is better when an 8 sample mean filter is used.

When the gain control signal is applied to the continuous wave, the audio signal can be displayed as in Figure 3.6. We see that there is no sound between the 5th and 6th second. This is due to the level of reverberation, which is below the noise level. When the audio signal from reverberation is mixed with the background-noise audio signal, the result is a realistic sound with no echoes from targets.

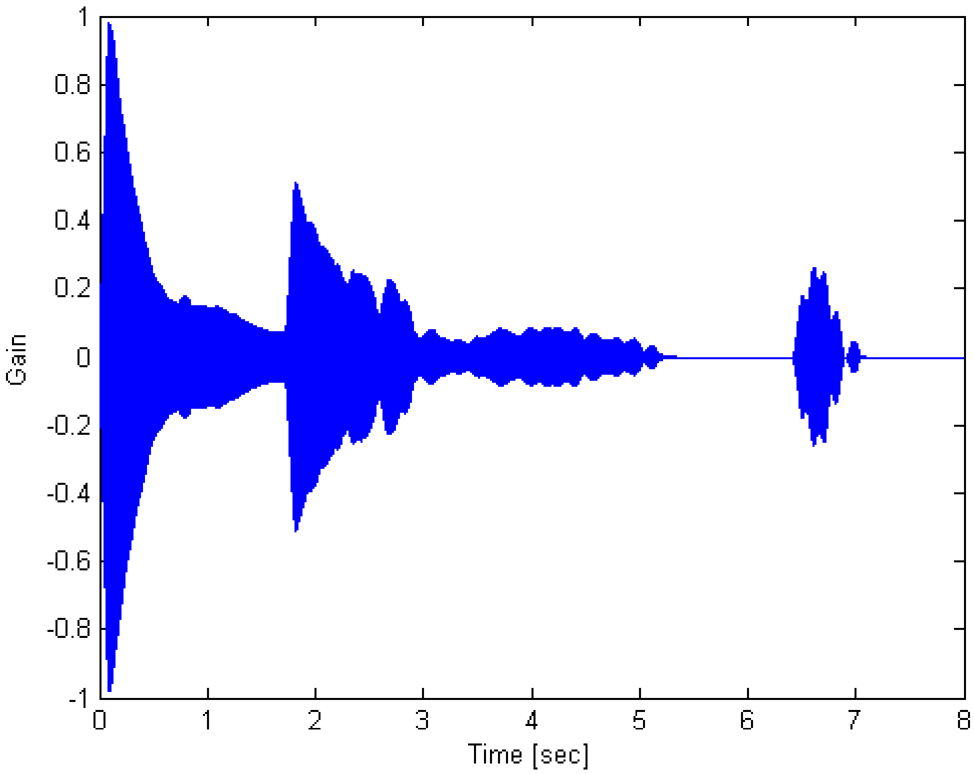


Figure 3.6 *The resulting audio signal of the reverberation in CW-mode. The envelope of the blue line is the intensity of the audio signal.*

3.3 The sound of targets

The echo from a target depends on several parameters, such as environment, aspect angle, size and shape. This simulated sonar demonstration does not include targets with all these parameters. However, targets can be included. The only properties needed are the range and the strength of the target. The range tells the algorithm the time to play an echo, and the strength tells the algorithm the strength of the echo compared to the reverberation.

3.4 Sound format

The sound format used is a one-channel pulse code modulation (PCM), with 16 bits dynamics and 8kHz samplings rate.

3.5 Summary of the sonar audio generation

The process of generating sonar audio, described in this document, focus on the background-noise of the audio. It is an important factor of making realistic sonar audio. The method described filters random noise with a pass-band filter with cut-off frequencies equal to real sonar audio. Further the background-noise is amplitude modulated to increase the realism and *feel* of the sound. The amplitude modulation is based on the current sea state. The background-noise method can be enhanced to take into account the self-noise and other passive contacts.

The audio signal containing the sound of reverberation is based on the transmitted pulse and the Lybin-result for that given direction. It is describes two different approaches depended on transmission-mode. The method can be enhanced to make better use of the actual values in the Lybin-result. Now the results are scaled between 0 and 1 depending on the maximum value in the result and the background-noise. This solution is not capable of reflecting the conditions in a decent manner.

The targets echo is included in the sonar audio based on their range and strength. This method can be enhanced greatly to include parameters like environment, aspect angle and object type.

The sonar audio generations gives an example of how to simulate sonar audio based on the parameters of a known sonar audio processing circuit and the reverberation in the area.

4 ECHO GENERATOR

The echo generator is planned implemented in the ASTT at KNM Tordenskjold. For targets defined by the ASTT, Lybin models the signal to noise/reverberation. For “false targets”, the model gives positions and echo levels of echoes based on modelled reverberation and noise. The echo generator both supports FM- and CW-processing. The same method is used to find false alarms for both FM and CW, but special considerations in the CW-case are made when computing echoes for defined targets.

The reverberation and signal to noise/reverb are obtained using Lybin. The calculations are made real time. Due to the high computational cost, methods of reducing the cost have been looked into. This chapter focuses on creating an echo cloud based on modelled reverberation and modelled signal to noise/reverb of specified targets. An echo cloud is a distribution of sonar detection in range and bearing relative the sonar.

4.1 Accuracy of the echo generator

The accuracy of the echo generation model depends mainly on the models resolution in range and bearing and the accuracy of the environmental data. The errors in the calculations, due to limited resolution and approximations, define an upper limit of accuracy. The demand for real time processing puts an *upper* limit on the model resolution, as greater resolution demands greater computation time. On the other hand, demands for realism puts a *lower* limit on the model resolution, since poor resolution would ultimately result in a near random distribution of echoes.

Consider a sonar range of 5km. With current technology[4] the best attainable resolution would be about 100m in range and 6^0 in bearing, with Lybin being run once every 0.1s, resulting in full 360^0 coverage in about 6 seconds. Regions[5] would range between areas of $1040m^2$ closest to the sonar and $54000m^2$ (100m in range, 540m angularly) at a range of 5km and $160000m^2$ (100m, 1600m) at 15km. The spatial error at large ranges is significant. Figure 4.1 shows a horizontal grid overlaying a depth contour map. Two different sets of range-bearing

---

[4] The best computers available at the time this report was written, was a Pentium 4 3GHz processor and 2Gb memory.

[5] A region is an area bounded by four neighbouring data points. The size of the region defines the resolution of the model.

resolutions are used. Notice how bathymetric features fall between radial lines in the right-hand figure. An improvement in angular resolution could be made at the expense of the range resolution, but that would in effect smear out the details in Lybin’s reverberation calculations and credible echoes would possibly be lost. Figure 4.2 shows three reverberation plots. The reverberation plots are for three equal runs of different radial resolutions: 25m, 100m and 500m. Figure 4.3 shows a ray trace plot with bottom and sound speed profiles. A peak in the terrain rises into the surface channel and contributes greatly to the reverberation. This contribution can be clearly seen when using resolutions of 25m and 100m, but vanishes when using a resolution of 500m. A significant amount of details are lost in the transition between resolutions of 25m and 100m. This results in neighbouring peaks to coincide, thus one echo is generated instead of two or more barely separated echoes.

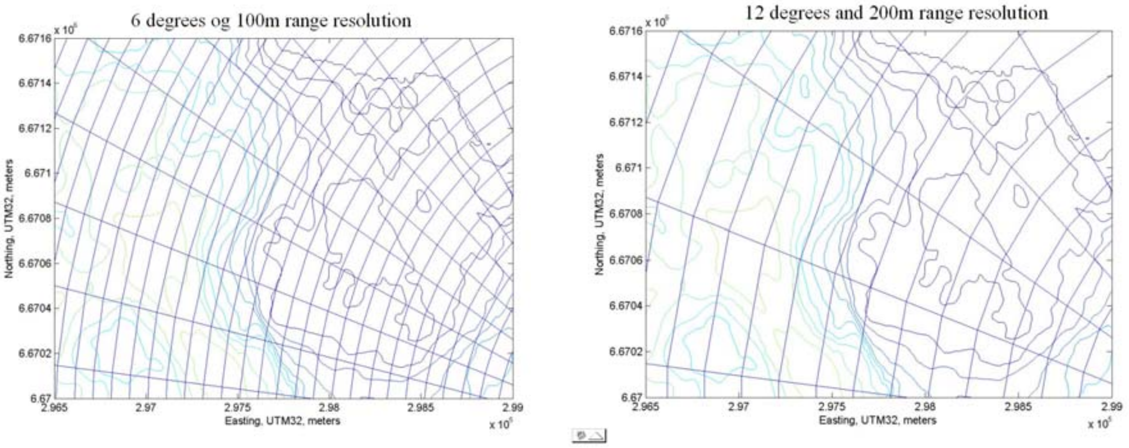


Figure 4.1 Comparison of two different sets of range and bearing resolutions. The radial lines are straight and represent the cross sections used in the Lybin modelling. The perpendicular lines represent the boundaries of the range cells.

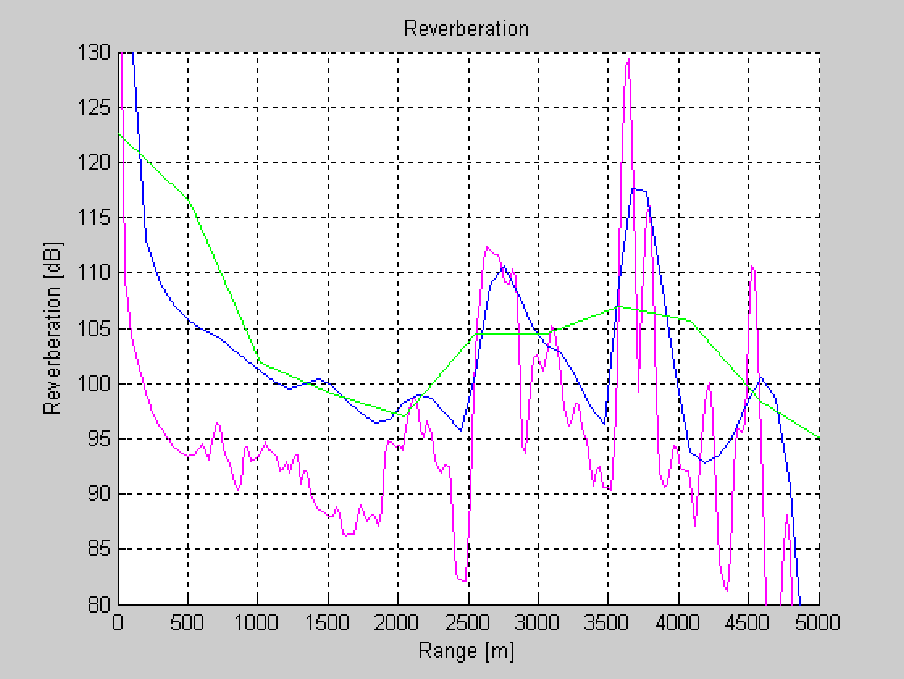


Figure 4.2 *Shows the total reverberation in dB for three Lybin runs using the same parameters except the radial resolution of the model: 25m (magenta), 100m (blue) and 500m (green).*

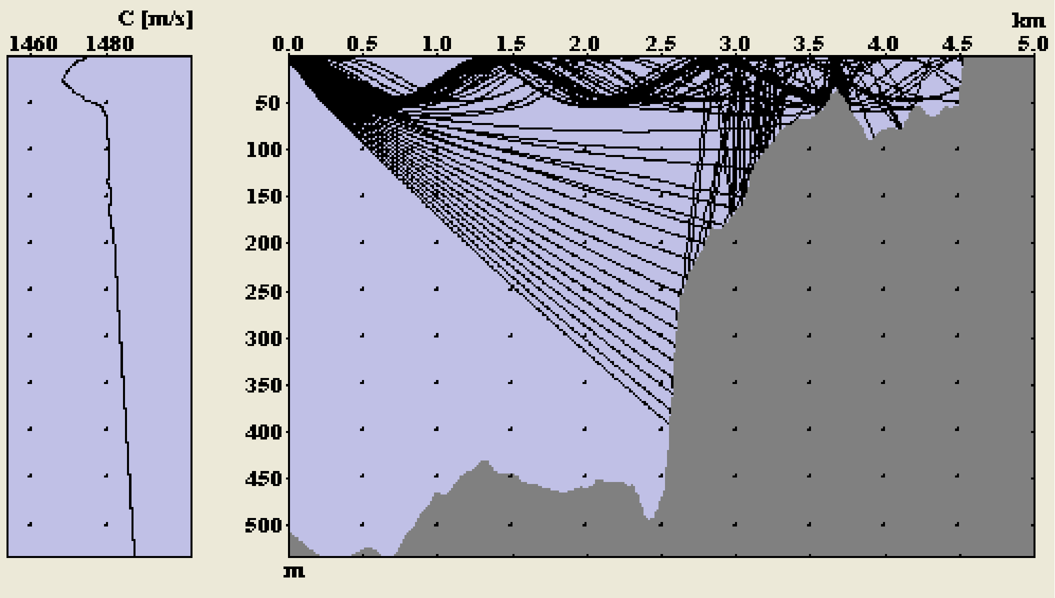


Figure 4.3 *Sound speed and bottom profile with ray trace of the main lobe of the beam.*

4.2 Input

The input data in echo generation model is almost the same as in Lybin. Elling Tveit et al give a complete list of the input data necessary for Lybin in appendix B1 in ref (2). For the purposes of the SIMSON echo generator model a far smaller list may be used. In addition to input data concerning the Lybin calculation some new parameters are introduced to control echo generation.

The model will be provided with the computational parameters automatically, such as the resolution and the amount of rays. The choice of such parameters may be based on a test of available computer resources. This test should be made during the initialisation of the scenario played in the ASTT and not slow the model down.

Parameters needed from sources outside the SIMSON model are sonar, ship, target and environmental parameters.

Most of the sonar parameters are defined in a database of available sonars and sonar settings. Some of the settings, e g tilt and sonar range[6], are selected by the sonar operator.

As with sonar parameters, the ship parameters are defined in a database of available ships.

The framework enveloping the echo generation model feeds it with positions and speeds of all targets within the sonar's range and also environmental parameters; bottom profiles and sound speed profiles etc. The framework also provides target strengths.

The echo generation model does not generate its own bottom profiles; the ASTT is able to do this itself. The model is fed with the necessary bottom profiles. The same applies for other environmental parameters such as wind speed and sound speed profiles. Such profiles range from the sonar position to the end of the sonar range defined by operator sonar settings. However, range-dependency of sound speed and wind speed is probably unnecessary for training purposes, since a single wind speed and single sound speed profile should offer adequate realism for training.

4.3 Output of the echo generator

A constant amount of echoes are generated for each ping, typically 200 echoes for the Oslo class frigates. These echoes are evenly distributed between bands encircling the sonar platform. The method of distributing echoes can be modified according to the echo distribution algorithm of the sonar in question. In this report the Spherion sonar aboard the Oslo class frigates has been used as an example.

The actual method of generating echoes is described in chapter 4.5. Several parameters are linked to the echoes. Each echo is tagged to define what kind of echo it is; bottom reverberation, surface reverberation, volume reverberation or real target. Echoes from real targets are linked to the target. A second output is the echoes' position relative the current location[7] of the frigate. Finally the echoes' strength is given, based on the normalized reverberation level in the relevant region.

The echoes will automatically be generated for each transmission based on the most recent Lybin reverberation calculations.

---

[6] The range of the sonar corresponds to the time between pings: $R = c*T/2$.

[7] The echoes are based on calculations made using the frigates earlier position, thus their positions must be moved according to the frigates recent motion.

4.4 Tricks to generate false alarms in real time

Several methods on reducing the computational cost have been looked into. The most obvious one is reducing the resolution, but as concluded in chapter 4.1, too coarse resolution would result in an almost random distribution of echoes. Other methods must therefore be used.

The following methods run Lybin in a parallel process on the same or a different computer:

Running Lybin in all directions is time consuming, the distribution of echoes among reverberation intensive regions is not. Therefore a new distribution can be made each time it is called for. That the echo positions are based on the same set of reverberation data is a minor inconvenience, since the reverberation levels using low resolution hardly changes at all from ping to ping, except at short ranges. The main problem with this solution is that a change in sonar settings would not be reflected in the echo distribution before an entire LYBIN dataset is processed.

An extension of the method is to run Lybin at shorter ranges more often than at maximum sonar range. That way, the sensitive reverberation levels at short range is updated more frequently than the stable reverberation levels at long ranges.

Another proposed solution is running Lybin in all directions, one at a time, with the most recent sonar settings and position. This means that the different directions are modelled with different sonar settings and from different positions. To further optimise the method, echoes are extracted immediately after the reverberation is calculated. This means that for a single ping echoes from different beams may have been processed from different sonar positions and settings. Even so, this is considered an improvement when compared to the method where reverberation in all directions is computed before the echoes are distributed.

4.5 Echo generation method

There are essentially two kinds of echoes; false and true echoes. False alarms are due to reverberation. True echoes are due to targets defined by the instructor. Lybin is used to find true and false alarms, but the method is different. It is assumed that modelled reverberation is computed in all directions and that Lybin is run in the directions of all targets for every ping. The methods will essentially be the same even if using one of the tricks presented in chapter 4.4.

4.5.1 False alarms

False alarms are computed using modelled reverberation in all directions. Since Lybin is a 2d model, see chapter 2, Lybin must be run *n* times to get a 3-dimensional[8] reverberation output.

The modelled reverberation is normalised using a split window technique:

$$A_n = \frac{A}{n}$$ Equation 2

---

[8] In literature this is often referred to as n*2-dimensional.

A_n is the normalised reverberation. *A* is the reverberation in the cell where the normalised reverberation is computed. $\bar{n}$ is the mean reverberation. The split windows are *m* range cells wide and separated by *p* cells. The mean values are found using reverberation values from the two windows.

After normalisation the reverberation is passed through a peak detector. All range cells with a normalised reverberation higher than a set threshold generate an echo. The echo range is set randomly within that range cell. The angular position of the echo is randomly displaced from the direction of that Lybin run by up to half the angle-separation between two Lybin runs.

$$R = r_i + rand * dr$$
$$\theta = \beta_j + (0.5 - rand) * d\beta \qquad \text{Equation 3}$$

R is the echo’s distance from the sonar. r_i is the distance from the sonar to the start of the *i*th range cell. dr is the width of a single range cell. θ is the angle relative north of a line from the sonar towards the echo. β is the direction relative north of the Lybin run generating the echo. $d\beta$ is the angular difference in the directions of two adjacent Lybin runs.

The method is illustrated in the following figures. Figure 4.4 shows the processing from Lybin reverberation output, to selected echo generating range cells in a single direction. Figure 4.5 shows how Lybin is run in all directions (along the black lines), and how the 360 degree reverberation level is found and then normalised. Figure 4.6 is an example echo cloud after thresholding of the normalised reverberation and randomising the echoes’ positions.

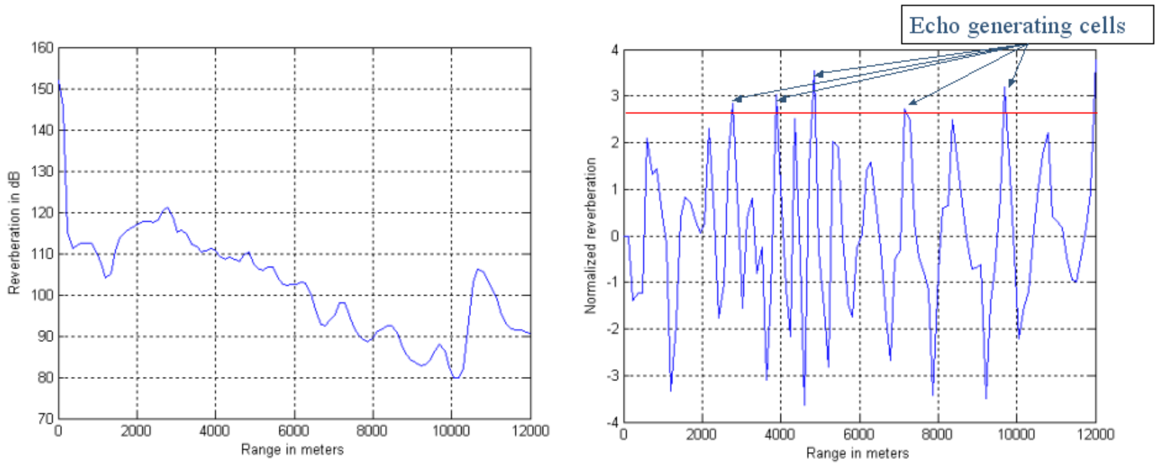


Figure 4.4 The left plot shows Lybin modelled reverberation in logarithmic scale. The right plot shows normalised reverberation based on the same reverberation as in the left plot. The horizontal red line in the right plot indicates the threshold used to determine echoes.

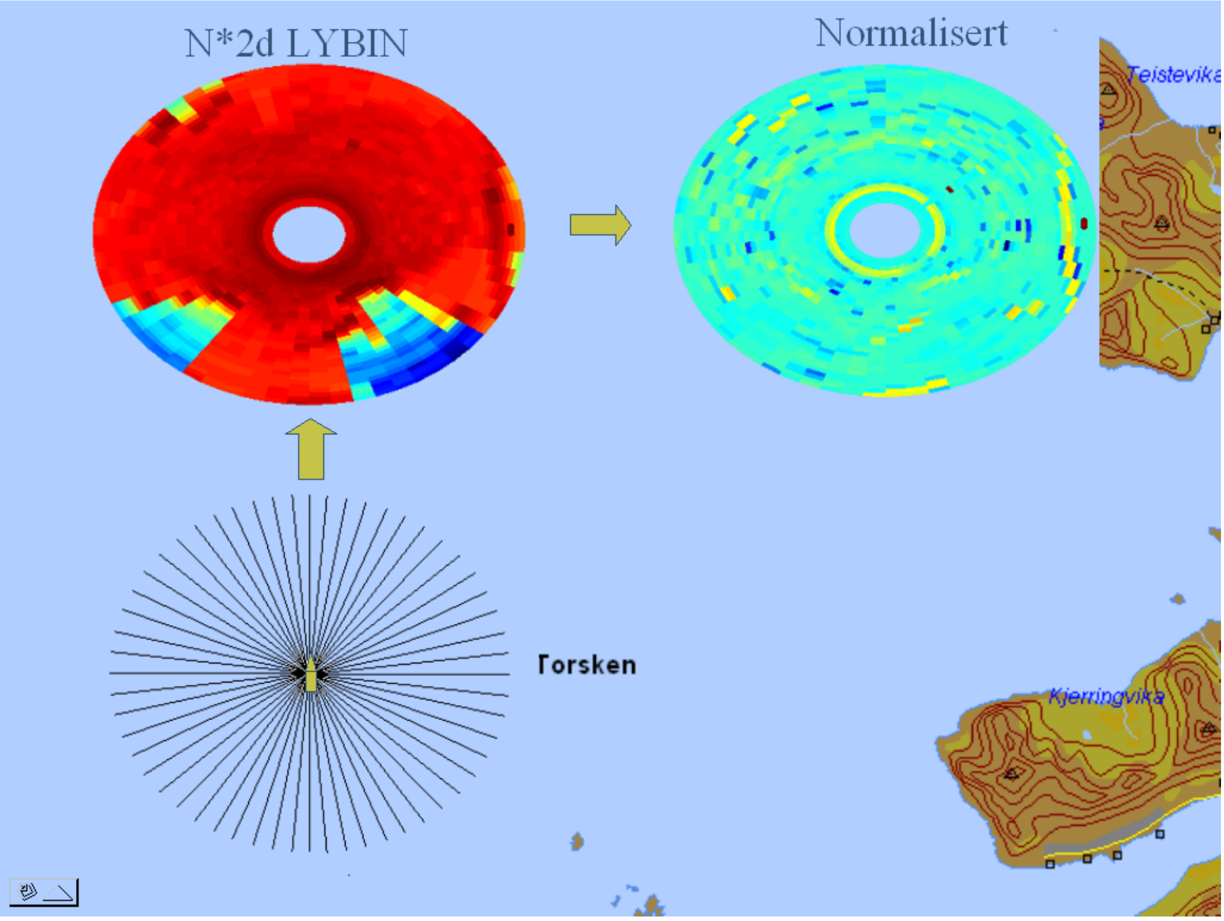


*Figure 4.5 Echo generation procedure from n*2d Lybin runs to normalised reverberation.*

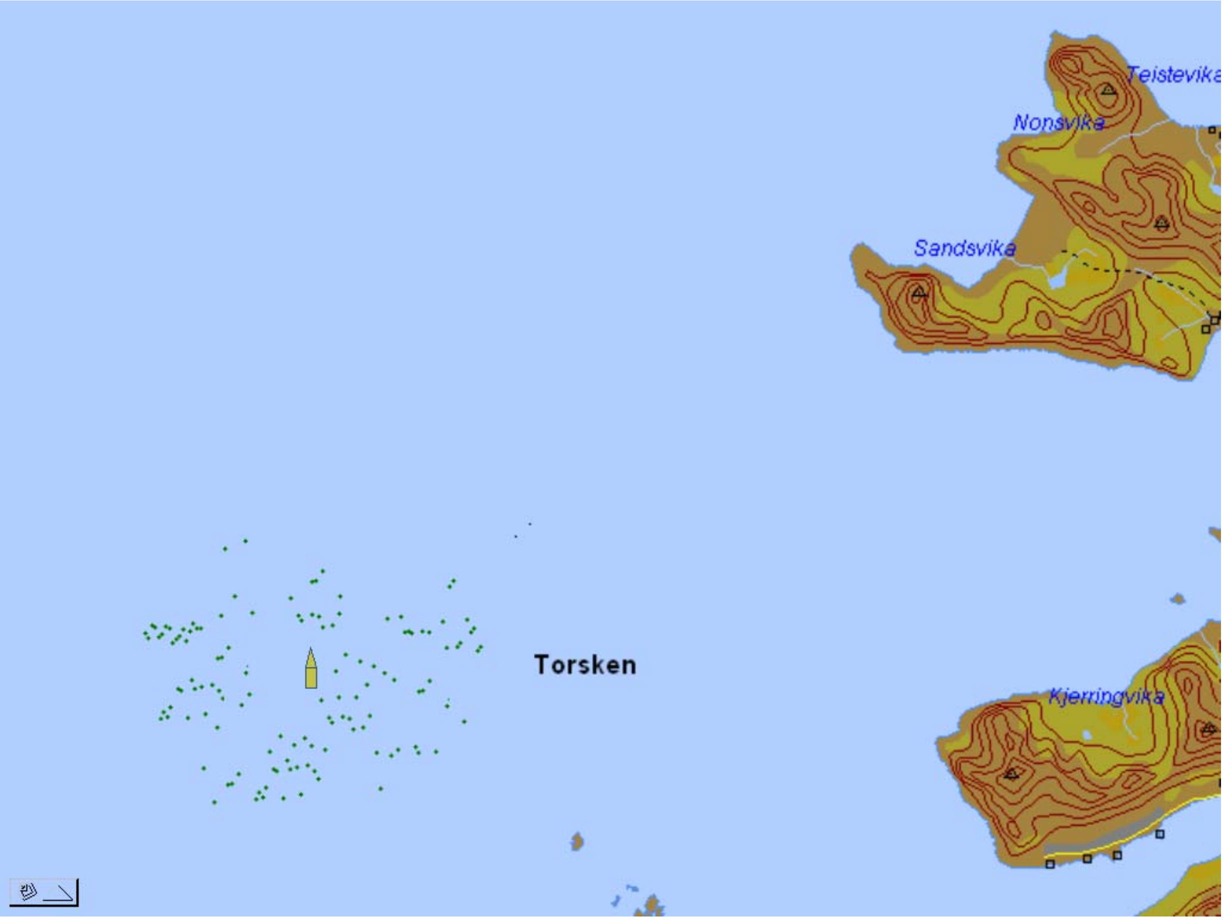


Figure 4.6 Example of generated echoes.

4.5.2 Echoes from targets

Each target is associated with a position, a speed and a target strength. For FM-processing the speed of the target is irrelevant. The ASTT-framework provides the model with all this information. Lybin is run for each target with all relevant input-data, such as sonar settings, sound speed and bottom profiles. The echo level of the submarine and the reverberation level in the submarine position are extracted from the output data. Two methods of determining whether there should be a submarine echo or not have been discussed.

1. The echo level of the target replaces the reverberation-output in the cell containing the submarine if it is higher than the reverberation.
2. If the signal-to-reverberation and noise level is higher than the detection threshold[9] an echo is generated at the target position.

The first method is probably the most correct, since a submarine echo will then have to go through the detector mechanism in the same way as other reflectors, such as sources of reverberation (e g bottom and surface). But the increased realism also increases the risk of not detecting a normally detectable target. The second method is therefore used.

---

[9] Refer to (5) for definition of detection threshold and echo level.

4.5.2.1 Target echoes and CW processing

This section suggests a method of including CW-processing in the echo generation model when determining the echo level of real targets. It is assumed that the CW-mode produces the same false alarm echoes as the FM-mode. This is a strong assumption, but it should work for training purposes where the demand for realism is not high. The method has not been implemented in the echo generator yet.

The theory presented in this section is mainly based on an unpublished paper by Svein Mjølsnes at NDLO/Sea. CW processing is a special case since the reverberation and noise obscuring the target is highly dependent on the speed of the target. In literature the angle-doppler speed space is usually divided into three different zones: the A-zone, B-zone and C-zone. If the target's doppler and angle relative the course of the sonar vessel places the target in the A-zone, then strong reverberation obscures it. In the B-zone the reverberation is weaker as the reverberation enters through the side lobes of the horizontal beam width. Finally, the sonar performance is noise-limited in the C-zone.

Figure 4.7 illustrates the doppler-zones. A target in the A-zone has very low Doppler-speed[10]. This is where all the reverberation that enters through the main lobe of the horizontal beam pattern is. Since the main lobe has a width (15 degrees in the example), the A-zone is wider for beams perpendicular to the vessel's course. This is due to geometry. Note that it is assumed that some reverberation sources may have speeds of up to 0.5 knots (e g surface waves). Since a CW signal has no frequency bandwidth, the reverberation is much higher than in the FM-case. Refer to (5) for more information on how frequency bandwidth influences reverberation. The B-zone contains reverberation entering through the side lobes of the horizontal receiver beam pattern. The reverberation in the B-zones is therefore suppressed according to the side lobe suppression of the window used in the horizontal beam forming. The C-zones are noise-limited since no source of reverberation is moving at higher speeds than 0.5knots. Table 4.1 summarizes the definitions and attributes of the different doppler-zones. The ship speed is v. β is the horizontal beam width of the receiver. ϕ is the angle of the beam relative the ship's course. v_{rev} is the speed of the fastest moving source of reverberation.

It is not complicated to implement the method. When determining the signal-to-noise and reverberation level of the defined targets (real targets; submarines, surface vessels etc) the noise and reverberation should be reduced according to what doppler-zone the target is in. E g if the target has a doppler speed that places it in the B-zone, then the reverberation should be reduced by the horizontal sidelobe level of the receiver before determining the signal-to-noise and reverberation level.

---

[10] Doppler speed is the radial speed of the target relative the sonar vessel. Positive Doppler-speed means that the target moves towards the sonar-vessel.

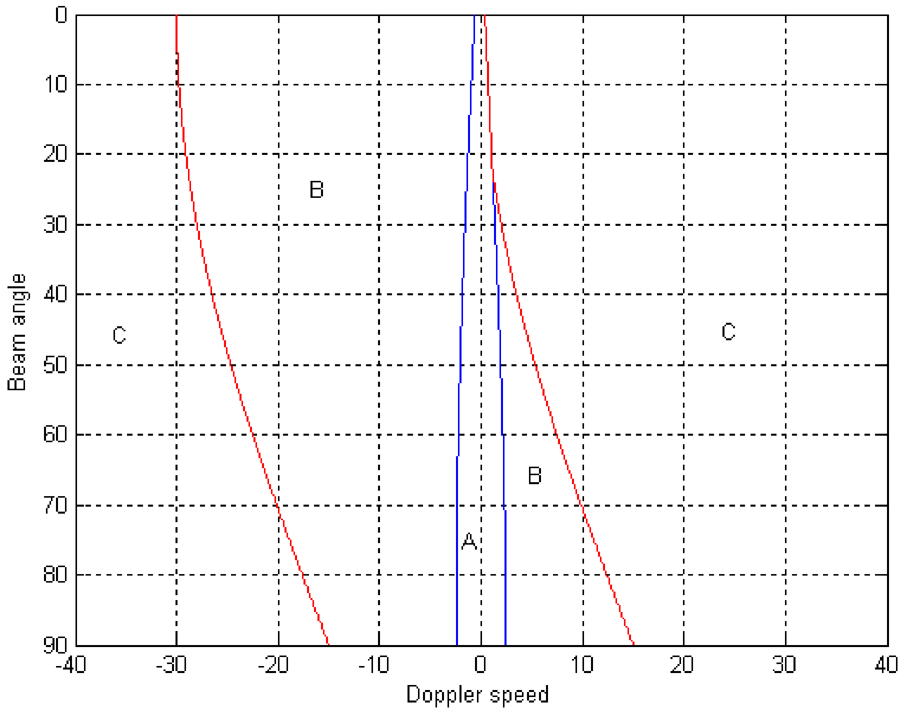


Figure 4.7 Illustration of doppler-zones. Along the x-axis is the doppler-speed of the target relative the sonar vessel. The Angle along the y-axis is the angle relative the ship's heading of the beam taking in the target. The blue lines bound the A-zone. The red and blue lines bound the B-zones. The C-zone is the remaining area. The ship moves at a speed of 15 knots.

Zone	**Reverberation and noise**	**Lower boundary**	**Higher boundary**
A	Noise and reverberation	$v(\cos(\phi - \frac{\beta}{2}) - \cos\phi) - v_{rev}$	$v(\cos(\phi + \frac{\beta}{2}) - \cos\phi) + v_{rev}$
B (right)	Noise and reduced reverberation (by sidelobe level)	$-v(1+\cos\phi) - v_{rev}$	$v(1-\cos\phi) + v_{rev}$
C	Noise	None	None

Table 4.1: Definitions of doppler-zones.

4.5.3 Horizontal beam forming

The sonar is a collection of hydrophones that record the reflections from a transmitted signal. The data obtained are beam formed with a certain horizontal and vertical beam pattern depending on the number of hydrophones and the algorithm used. Each beam corresponds to a sonar channel. The beam formed data is match filtered and normalized before the echoes are generated.

Lybin takes into account the vertical beam pattern of the sonar when computing the reverberation and signal excess, but since it is a 2d model it does not fully take into account the horizontal beam pattern. The directivity index gives an indication of the reverberation and noise reducing effect of the horizontal beam pattern. Figure 4.8 shows an example of a sonars horizontal beam pattern. It is obvious that the directivity of each channel is limited; if the side lobes hit reverberation intensive areas then their contribution to the received signal may be greater than the main lobes contribution. For instance if a submarine is at close range within the surface duct, then the echo level of the submarine might be stronger than the reverberation in all channels at that range. To compensate for this effect the reverberation in all directions and signal excess of all targets should be taken into account when computing the received signal for each channel using the horizontal beam pattern of the sonar used. Note that the same signal excess and reverberation calculations are used for all channels, so the extra computation time required is acceptable. However, the increased realism due to horizontal beam forming of the modelled reverberation is low and therefore unnecessary for training purposes. Instead it is assumed that the significant reverberation originates from the centre of the main lobe.

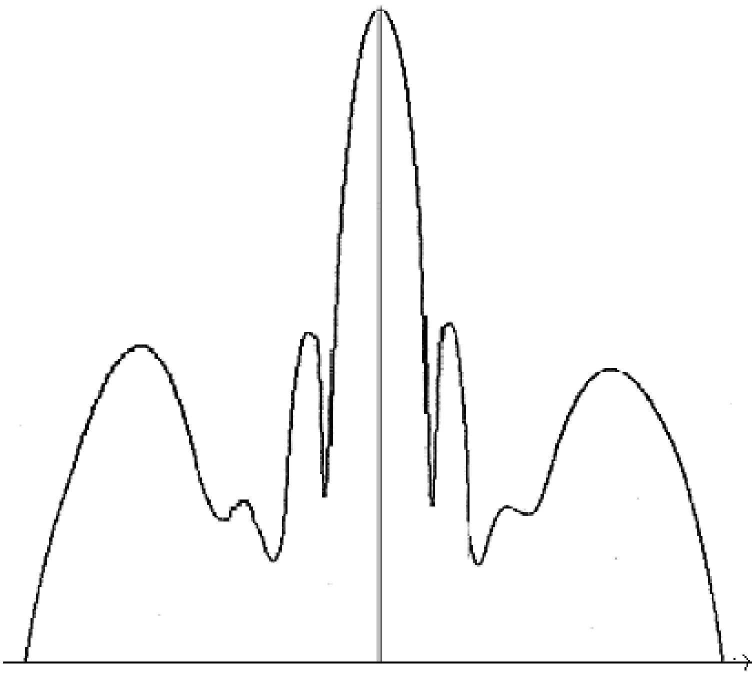


Figure 4.8 An example of a sonars horizontal beam pattern.

4.5.4 Echo distribution

This section describes a method of distributing echoes in a realistic way for the Spherion sonar aboard the Oslo-class frigates. Note that the method applies for this sonar only, but that small modifications are needed to include other sonars. Note also that the third trick mentioned in chapter 4.4 limits the distribution method. Even so, the trick can be used without jeopardizing the distribution.

The distribution of echoes among reverberation[11] intensive regions[12] in the sonar simulation module is partly random. The echoes, typically 200, are first evenly distributed among bands encircling the frigate, then distributed randomly between regions within a band. The last distribution is random, weighted by the normalized reverberation level of the region. One region may only be distributed a single echo. Figure 1.3 illustrates. The area, which the sonar

---

[11] In this section a reverberation intensive region corresponds to a region with a strong received signal, due to reverberation or targets.

[12] A region is defined by the resolution in range and bearing used in the model.

covers, is here divided into 24 bands. The inner black area, represents the sonars blind zone due to the transmission, it has been exaggerated. In this example four radial lines separated by 90^0, and seven concentric circles separated by a constant range define the bands. In the examples shown in chapter 0 the pulse length in meters is used as the width of bands. The number of regions within a band depends on the resolution used. Each region may only contain one echo, thus a band may only contain a number of echoes equal to the number of regions within the band. All bands must contain a preset number of echoes. In the example in figure 1.3, 48 echoes have been distributed.

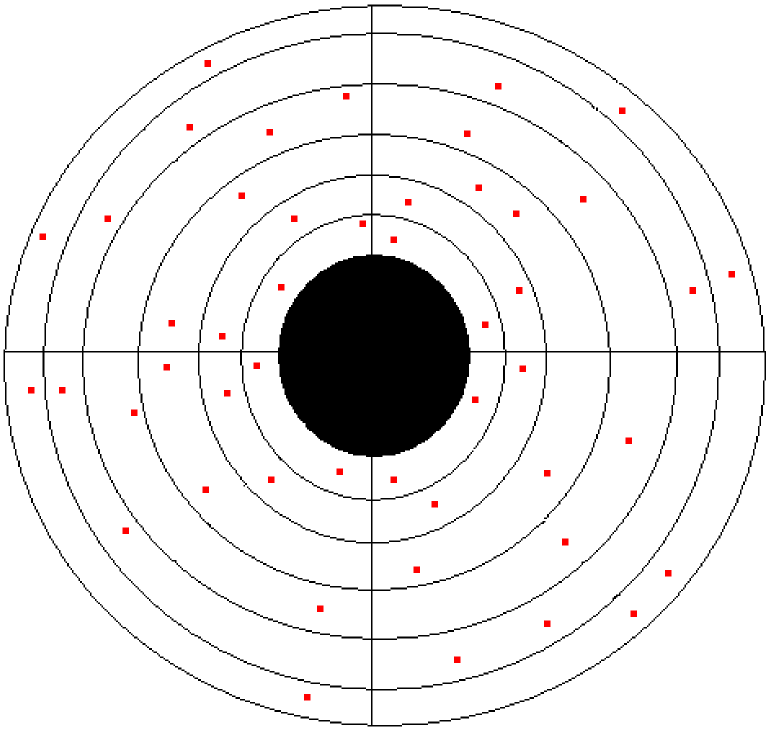


Figure 4.9 Echo distribution among regions and bands.

The Spherion sonar used on the Oslo class frigates use an interpolation technique to estimate the direction of echoes. The three beams surrounding the echo are used. The echo is placed within the centre beam, but the unnormalized reverberations of the other two beams at the same range are used as weights when computing the position within the beam. The echo is placed closest to the strongest neighbouring beam. A similar approach could be used to estimate the ranges and bearings of the modelled echoes, by using the cells surrounding[13] the echo. This technique could be used as an extension of the randomisation technique described above. The echoes are still randomly distributed between regions but are placed within that region according to the interpolation technique. Note that the rapid sampling of the Spherion sonar results in a far better radial resolution than in the modelling. Thus the Spherion sonar has no need to interpolate the range of echoes.

As an option, to avoid stochastic effects the strongest echoes of a single band may be chosen instead of a random distribution. In the studies in chapter 0, this less stochastic method is used.

---

[13] That is the cell containing the echo and the neighbouring cells with increased and decreased range and angle.

4.6 Examples of echo generation

The sonar simulation module is supposed to model echoes from the sonars delivered to the Nansen class frigates. Alas, no accurate information of the sonar's beam pattern is available yet. Instead the old Spherion sonar aboard the Oslo-class frigates is used. Table 4.2 shows the sonar and target parameters used. The beam characteristics are for the vertical beam pattern. The horizontal beam pattern is not taken into account.

Sonar depth	5m		Source level	217 dB
Tilt, sender	0^0		Directivity	23 dB
Tilt, receiver	0^0		Target strength	0 dB
Sidelobe, sender	-15dB		Pulse length	varies
Sidelobe receiver	-18dB		Frequency	6.5kHz
Beam width, sender	17^0		Bandwidth	500Hz
Beam width, receiver	13.5^0			

Table 4.2 Sonar and target parameters used during modelling.

Consider a case where the time between pings is varied between 5s and 30s and the pulse length between 300ms and 1200ms. Then the range of possible detection varies between 4km (min 0.2km) and 23km (min 0.9km). The number of cells in range must be varied from run to run to keep the initial demand of a 100m resolution in range. The number of cells in depth is kept at 50 cells even though the depth varies.

The mixed interpolation and randomisation technique described in chapter 4.5.4 is used to compute the positions of the echoes.

All the following scenarios use bottom and sound speed data from the district outside Marsteinen. The sound speed profiles used were obtained from XBT drops from the NAT III trial in 2002.

4.6.1 Flat terrain, targets in surface duct

In the first experiment the frigate hunts for a submarine at close range. The submarine is in the surface duct. The sound speed profile is shown in Figure 4.10. The depth of the sonar is 5m and the submarines depth is indicated by a circle at 30m depth. The vessels are located in a fairly flat region as shown in Figure 4.11. A semi-hard bottom is used (Lybin bottom type 3). The sea state is low, using a wind speed of 2m/s. The pulse length is 300ms and seven seconds separate the pings, resulting in a sonar range between .5km and 5km.

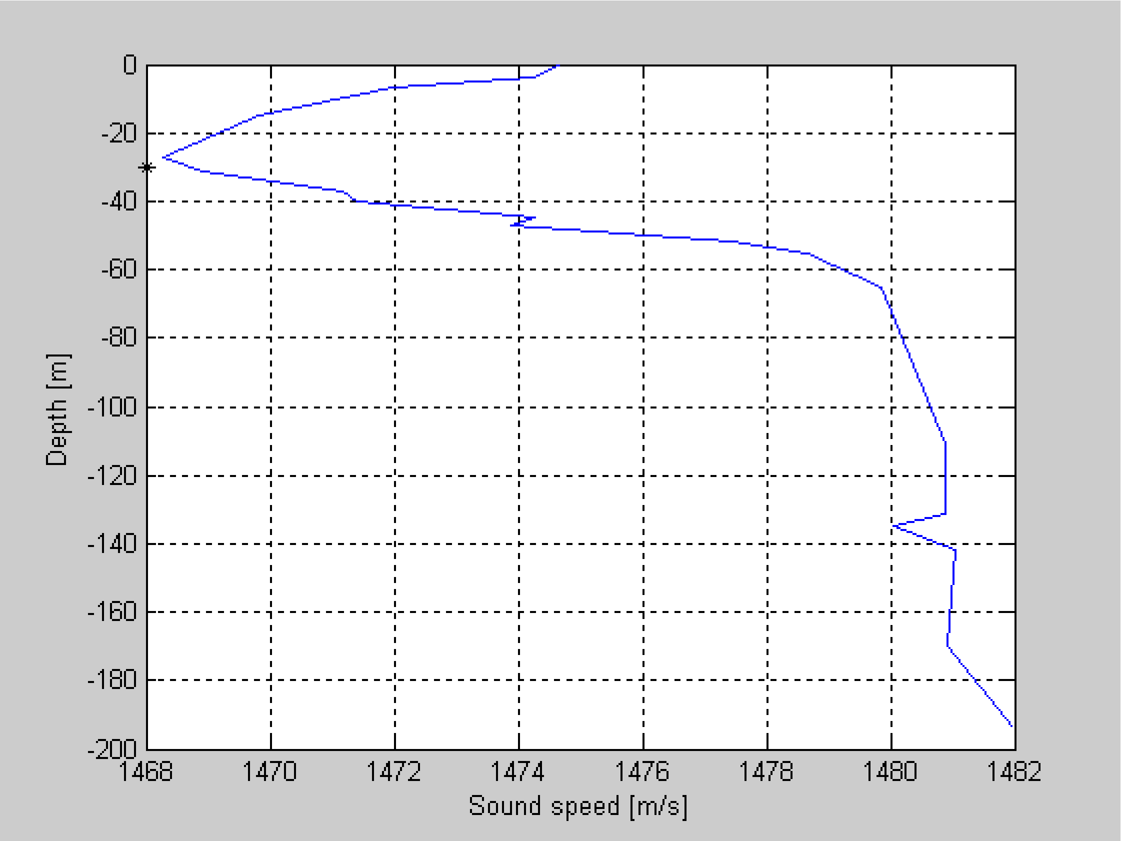


Figure 4.10 Sound speed profile used in the modelling.

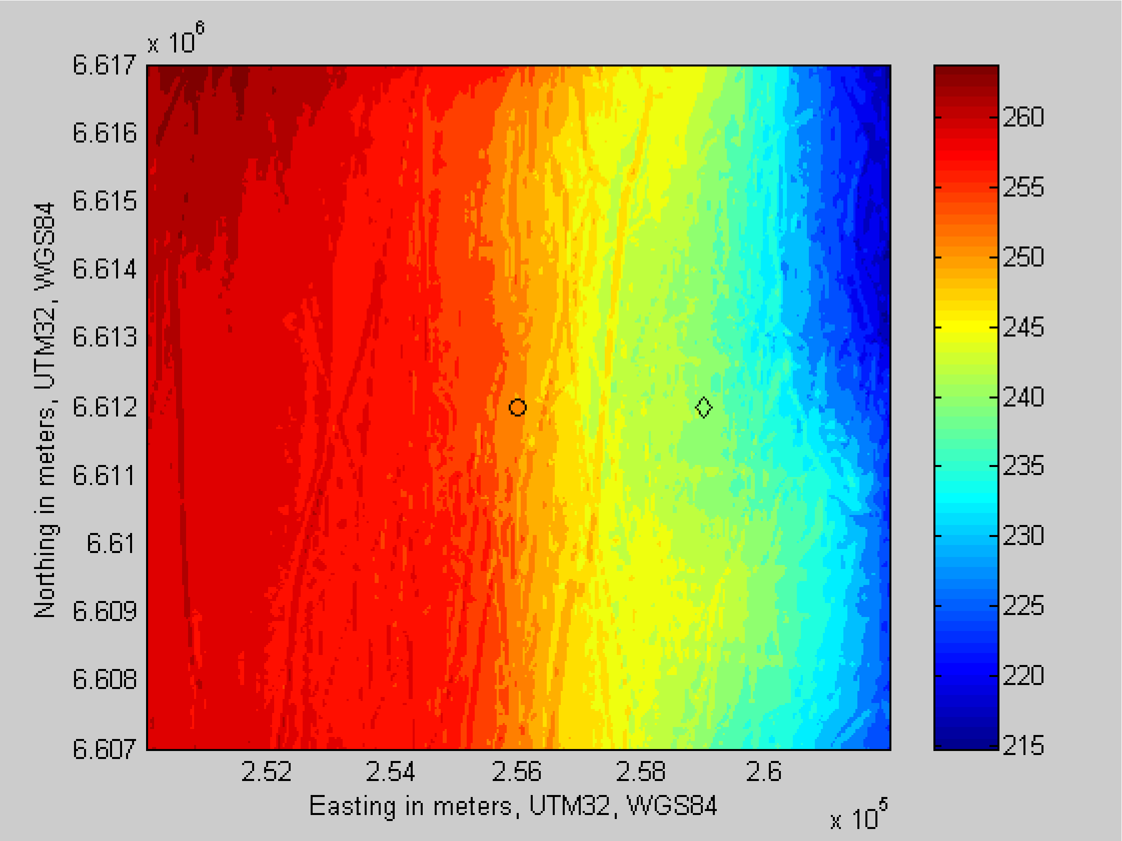


Figure 4.11 Detailed map of depths in the region of the study. The black circle indicates the pinging position. The black diamond shows the submarines position, while the black star shows the surface vessels position.

Two targets are used; one surface vessel with keel depth of 5m and target strength of 20dB, and one submarine submerged at 30m depth and with a target strength of 10dB.

Lybin is run for every sixth degree up to a range of 5km using a radial resolution of 100m. Figure 4.12 shows the echo distribution.

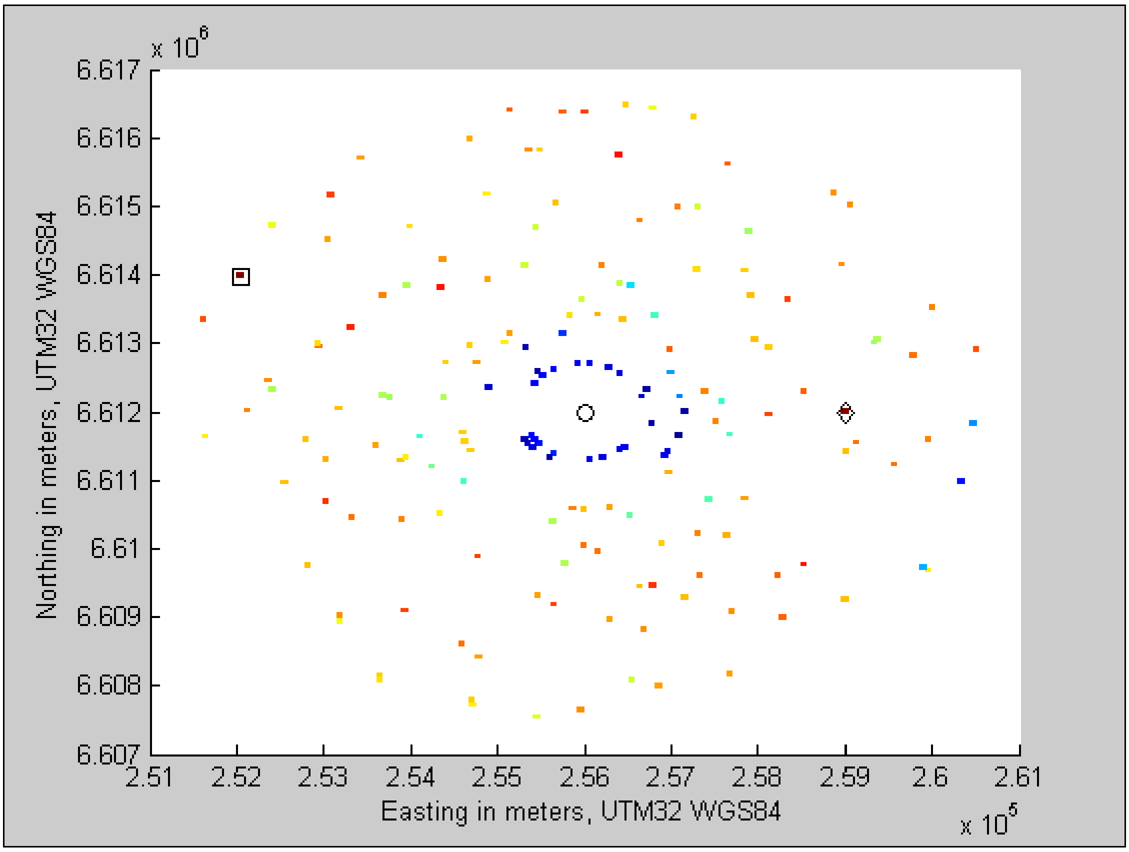


Figure 4.12 Echo distribution for a single ping. The colour of the echoes indicates the strength; red is strong, blue is weak

Both targets give strong echoes. Their positions are indicated by a square for the surface target and a diamond for the submarine in Figure 4.12. The main reasons for their high echo levels are their relatively high target strengths combined with being located in the surface channel. The surface target's echo is strongest with an SNR of 46dB. It should be easily detected. The submarine, on the other hand, has an SNR of 15dB and is therefore harder to detect. A decrease of the target strength of the submarine to 0dB results in an SNR of 5dB and no echo.

At about 600m range a circle of echoes surrounds the pinging position. The echoes are weak and appear due to peaks in the bottom reverberation where the first sidelobe hits the bottom. Note that since the echoes are distributed equally between bands some of the echoes shown may be weaker than excluded echoes. The SPHERION sonar have ways of dealing with this problem, a filter that removes echoes from large reflectors. This filter would also remove the echoes from the sidelobe bottom reflection.

Figure 4.13 shows the echo distribution for an identical scenario as in Figure 4.12. The only difference is that the angular resolution is improved to 1^0. Both targets yield echoes of approximately the same strength as in the previous run (SNR's of 16dB and 44dB).

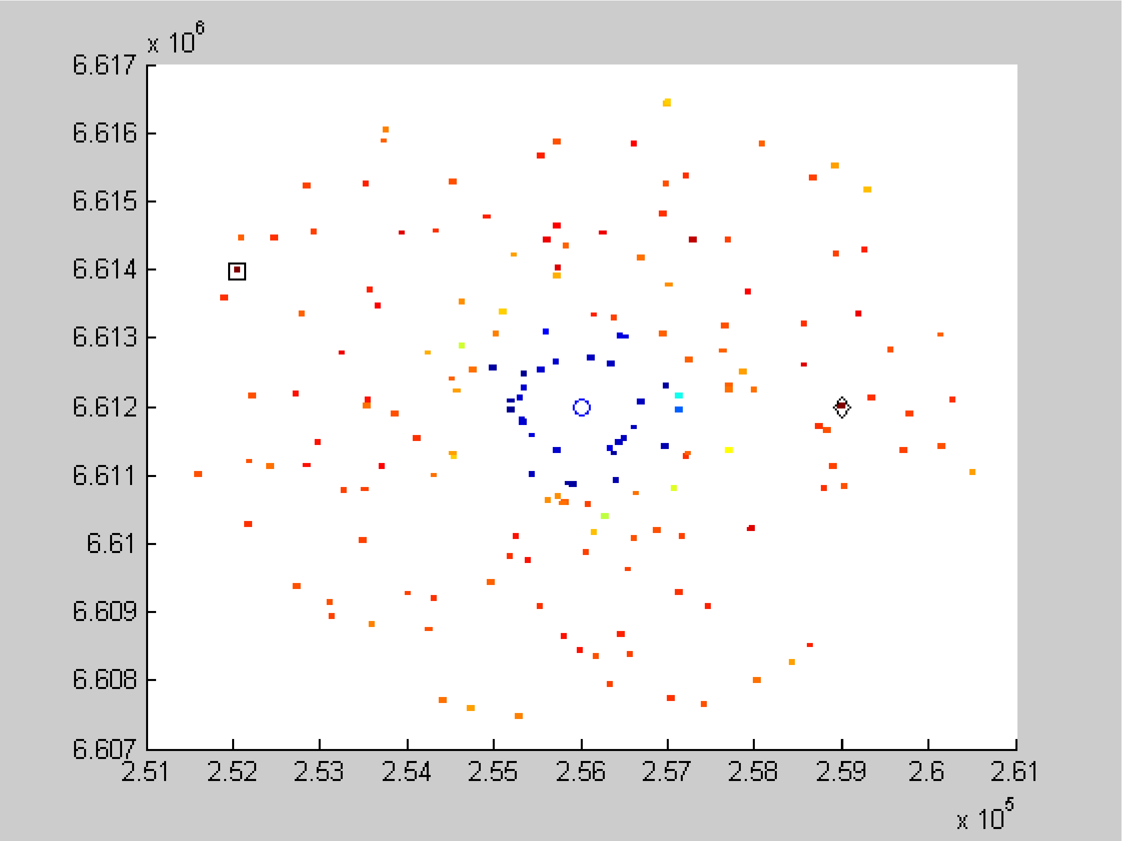


Figure 4.13 Echo distribution using the echo generator with an angular resolution of 1^0.

4.6.2 Undulating bottom

In this study the frigate searches for slow moving submarines hidden in a bottom reverberation intensive region. The frigate covers a large area and uses long pulse lengths, 900ms, and 15s between pings.

The sound speed profile shown in Figure 4.10 is used. Figure 4.14 shows the map of depths in the area of the run. A hard bottom is used (Lybin bottom type 3) and the wind speed used is 5m/s.

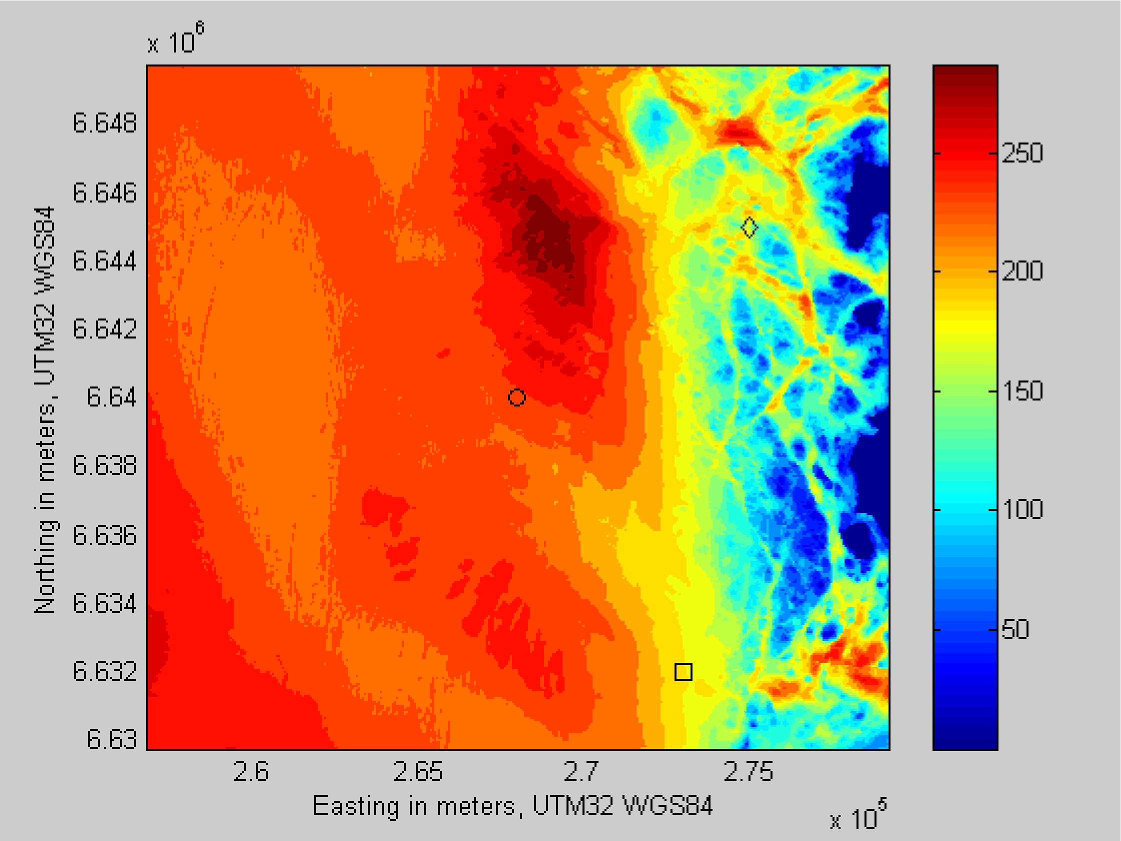


Figure 4.14 Detailed map of depths in the vicinity of the pinging vessel and targets. The frigates position is indicated by a circle. The targets' positions are shown as a square and a diamond.

There are two submerged targets. Each target is a submarine with target strength of 0dB. The first submarine (diamond in plots) is within the surface channel at a depth of 30m. The second submarine (square in plots) is at a 100m depth.

Figure 4.15 shows the echo distribution for the case described above. Only the shallowest target yields an echo. This echo has an SNR of 7dB. The other target is below the surface duct and remains undetected.

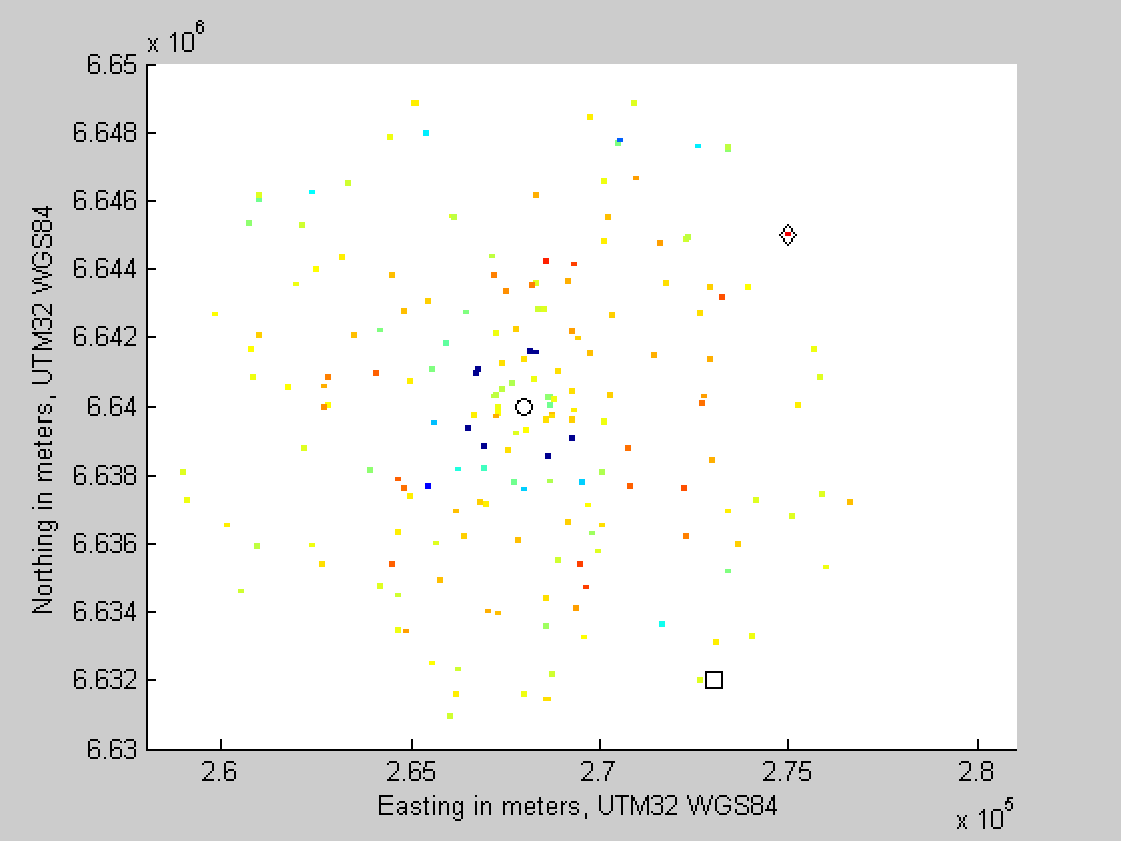


Figure 4.15 Echo distribution plot for a single ping.

5 TRACKING

The tracking algorithm implemented in the simulator is of a nearest neighbour kind. The algorithm is recursive and based on a Kalman-filter for estimation. The algorithm is cost-efficient and has runtime proportional to the number of echoes per transmission to a maximum of 1000 simultaneous tracks. When the maximum number of track is reached, it is presumed to have a constant runtime.

The state-model used predicts linear movement, but with some suspected system noise (manoeuvring and other accelerations). Echoes are linked to existing tracks by using the nearest neighbour to the predicted position. The echo to be linked to a track must reside within a sigma-gate. If there are no echoes, the target is presumed undetected and the predicted position is used as the state estimation. The sigma-gate represents the predicted uncertainty of the prediction, which in turn is based on the uncertainty of the echo. The gate-size in the implementation is 3σ (sigma), which is a quite large gate. This yields a probability of 99% that the new echo from the target is resided within the gate. On the other hand, the amount of false alarms within the gate will be quite frequent. To compensate for the probability that a false echo will be linked to a track that is tracking a real target, it is implemented an extra property to the echoes that allow the tracker to check if either of the echoes within the gate is from a target. This is a benefit of operating in a simulated environment. If this property is assigned and the target is detectable, the algorithm is able to track a target through dense clutter.

Then a track is formed and the algorithm is estimating its state variables, we say that the track has entered maintenance-mode. Before this mode, the track has to be initiated and is thus in an initiation-mode. In this tracker the echoes unused by tracks in maintenance-mode are available to tracks in initiation-mode. These are echoes that are possible new tracks. If one or more echoes from the next transmission are placed within the maximum distance that a target can travel between transmissions, limited by a defined maximum velocity of targets, then a new track is ready to enter maintenance-mode with the nearest new echo defining the velocity-vector of the track. The unused echoes from the previous transmission are deleted, and the unused echoes from the current transmission are saved as tracks in initiation-mode.

Tracks in maintenance-mode must fulfil some criteria. These are depended on velocity and number of lost updates. The algorithm has user defined maximum and minimum allowed velocity for a track. If a track exceeds one of these criteria, it will be deleted. If a track, in lack of any echoes, has used the predicted position more than 2 times in a row, then the track will be deleted.

6 SONAR SIMULATION OUTPUT

The central features of the sonar simulation module are the generation of tracks and audio.

The method of generating echoes is described in chapter 4.4. The tracking algorithm is described in chapter 5. Several parameters are linked to the tracks. Each track is tagged to define what kind of echo it is; bottom reverberation, surface reverberation, volume reverberation or real target. A second output is the tracks' position relative the current location of the frigate. Finally the track probability is given, see chapter 5.

Another feature is the generation of audio. The operator may choose a sonar channel[14] and listen to the returning signal using headphones. The returning signal is completely based on Lybin computed reverberation and noise unless a target is present within the channel. A description of how audio is generated is given in chapter 3.

The current ASTT sonar simulation module also supports echo structure plots. The sonar operator may study the time series of an echo from a selected track. A simple method is used; echo structures of typical reflectors such as a submarine, a surface vessel, the surface and bottom features are contained in a data base. The source of every echo is known. The method randomly selects an echo structure according to the source of the echo. Since Lybin is not yet able to compute the echo structure, this method will be unchanged in the new sonar simulation module.

---

[14] A sonar channel corresponds to a horizontal receiver beam, see ref (4).

7 CONCLUSION

A functional sonar simulation module has been developed. The module generates output in form of sonar audio and tracks. The tracks are based on echoes from surface and subsurface vessels, and on false alarms from terrain. It uses the Norwegian Navy’s acoustic ray tracing model Lybin, the sonar equations and a basic detection algorithm to determine the echoes. Lybin is also used to generate the reverberation component of the sonar audio.

Methods running the module in real-time are proposed. However, even though the sonar operator gets the data in real time, some of the data presented origins from modelling using old sonar positions and parameters. In most cases, the sonar operator should be unable to see this. Increased processing power is assumed to alleviate this problem.

APPENDIX

A DEFINITIONS

Angular resolution	The angular resolution is the angular separation between two neighbouring Lybin runs.
Audio	Beam data played as sound on the operators head phones.
CW	Continuous wave. A single-frequency sinusoidal signal.
Depth cell	A depth cell is a depth-segment in Lybin.
Doppler-speed	Doppler speed is the radial speed of the target relative the sonar vessel. Positive Doppler-speed means that the target moves towards the sonar-vessel.
Echo	A reflected replica of the initial transmission, regardless of the type of reflector.
FM	A sinusoid signal consisting of an increasing (up-chirp) or decreasing (down-chirp) frequency with time.
LYBIN	LYBIN is an acoustical raytrace model developed and owned by the Royal Norwegian Navy.
Normalisation	A mathematical method of enhancing portions of a time-series with strong gradients.
PCM	Pulse code Modulation
Range cell	A range cell is a range-segment in Lybin.
Range resolution	The width of a range cell (100m in this report).
Region	A region is a range cell in length and has an angular width equal to the angular resolution. It is centred on the line Lybin runs along.
Reverberation	Received beam level due to backscatter from the bottom, surface and volume inhomogeneties.
Sound speed profile	The sound speed as a function of depth.
Track	A path running though more than two echoes following certain rules on echo-seperation in time and position.
Tracker	An algorithm using echoes to generate tracks.
Transmission	Acoustic sending of a pulse from the sonar.
Transmission loss	The intensity loss due to propagation of waves.
XBT	Expendable bathy thermometer. A device to measure the sea temperature as a function of depth.

References

(1) Karl Thomas Hjelmervik, Amund Gjersøe og Svein Alsterberg (2006): Sonar Simulation Module for Land-based Sonar Operator Training, Underwater Defence Technology Conference and Exhibition, Hamburg.

(2) Elin Dombestein, Karl Thomas Hjelmervik, Elling Tveit (2003): Proposed use of LYBIN in project SIMSON, 2003/00950, Unclassified

(3) Svein Alsterberg, Elin Dombestein (2006): LYBIN XML grensesnitt versjon 1, 2006/00266, Unclassified

(4) Jon Wegge, Elin Dombestein, Amund L Gjersøe, Karl Thomas Hjelmervik og Elling Tveit (2003): Active Sonar Clutter prediction, Underwater Defence Technology Conference and Exhibition, Malmø.

(5) A. D. Waite (2002): “SONAR for Practicing Engineers”, 3rd ed., John Wiley and Sons Ltd

(6) Elin Dombestein, Karl Thomas Hjelmervik (2004): Analysis of the NAT III experiments – Modelling Assumptions, 2004/01083, Unclassified

(8) Jon Wegge (2003/01928): OVERALL DESCRIPTION OF AN ANALYSIS AND SIMULATION TOOL FOR ACOUSTIC ASW SENSORS, Unclassified