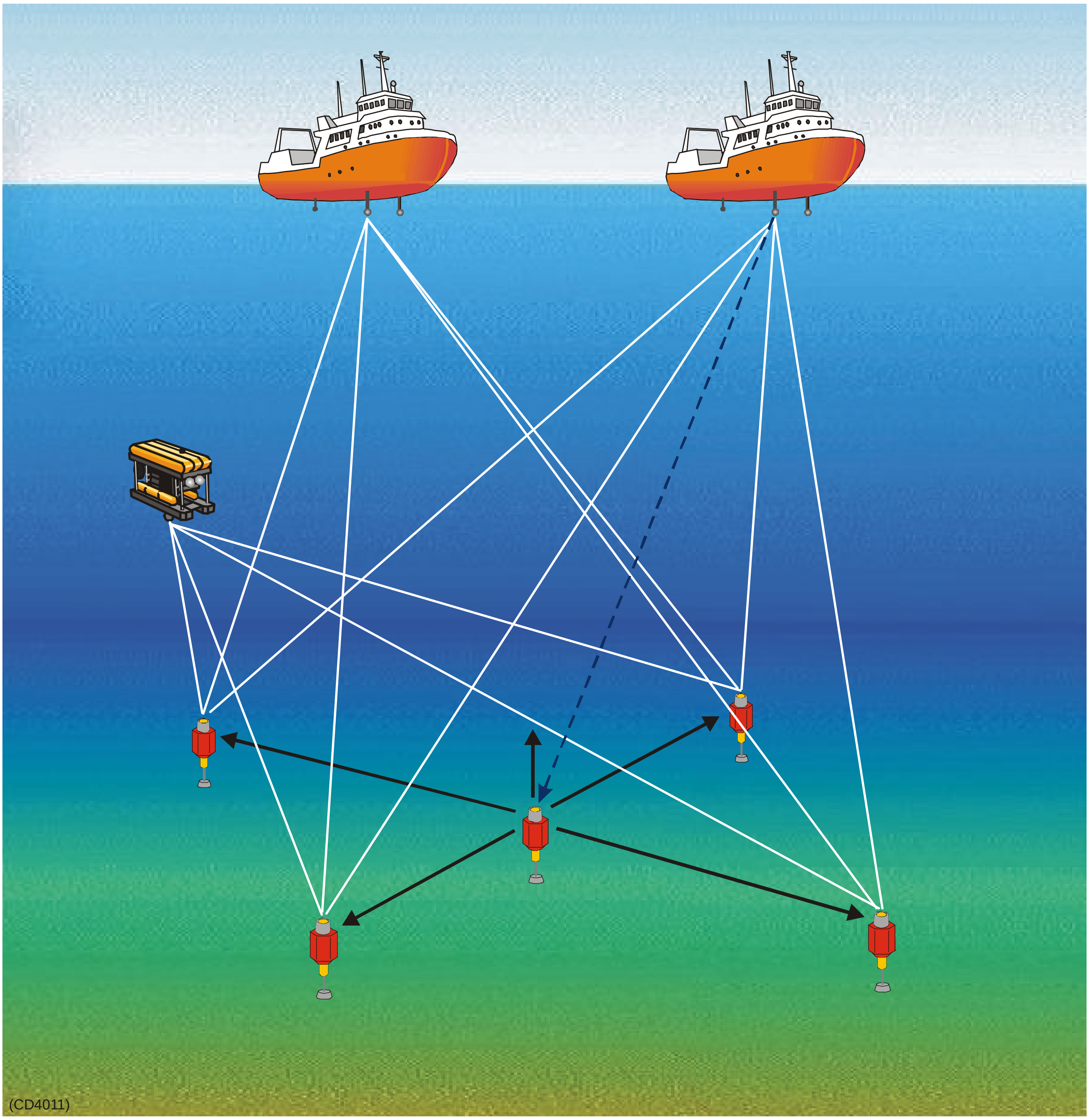
Instruction manual

Introduction to underwater acoustics



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Introduction to underwater acoustics

Note

Warning

The equipment to which this manual applies must only be used for the purpose for which it was designed. Improper use or maintenance may cause damage to the equipment or injury to personnel. The user must be familiar with the contents of the appropriate manuals before attempting to install, operate or maintain the equipment.

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Rev. A	Original version prepared for Offshore Europe in Aberdeen, September 10th, 1985
Rev. B	Modified and improved with additional information inserted. Ref EM 857-164237B.

1 INTRODUCTION

1.1 General

Acoustic sound transmission represents the basic techniques for underwater navigation, telemetry, echo sounder and sonar systems. Common for these systems are the use of underwater pressure wave signals that propagates with a speed of approximately 1500 m/s through the water.

When the pressure wave hits the sea bottom or another object, a reflected signal is transmitted back and detected by the system. The reflected signal contains information about the nature of the reflected object.

For a navigation and telemetry system the communication is based on an active exchange of acoustic signals between two or more intelligent units.

1.2 Transmission

Transmission of underwater signals is influenced by a number of physical limitations, which together limits the range, accuracy and reliability of a navigation or telemetry system.

The factors which will be described in the following are:

- Transmitted power
- Transmission loss
- Transducer configuration
- Directivity and bandwidth of receiver
- Environmental noise
- Requirements to signal/noise ratio for reliable signal detection
- Ray-bending and reflected signals

The signal-to-noise ratio obtained can be calculated by the sonar equation.

→ *The different parameters involved are illustrated in figure 1.*

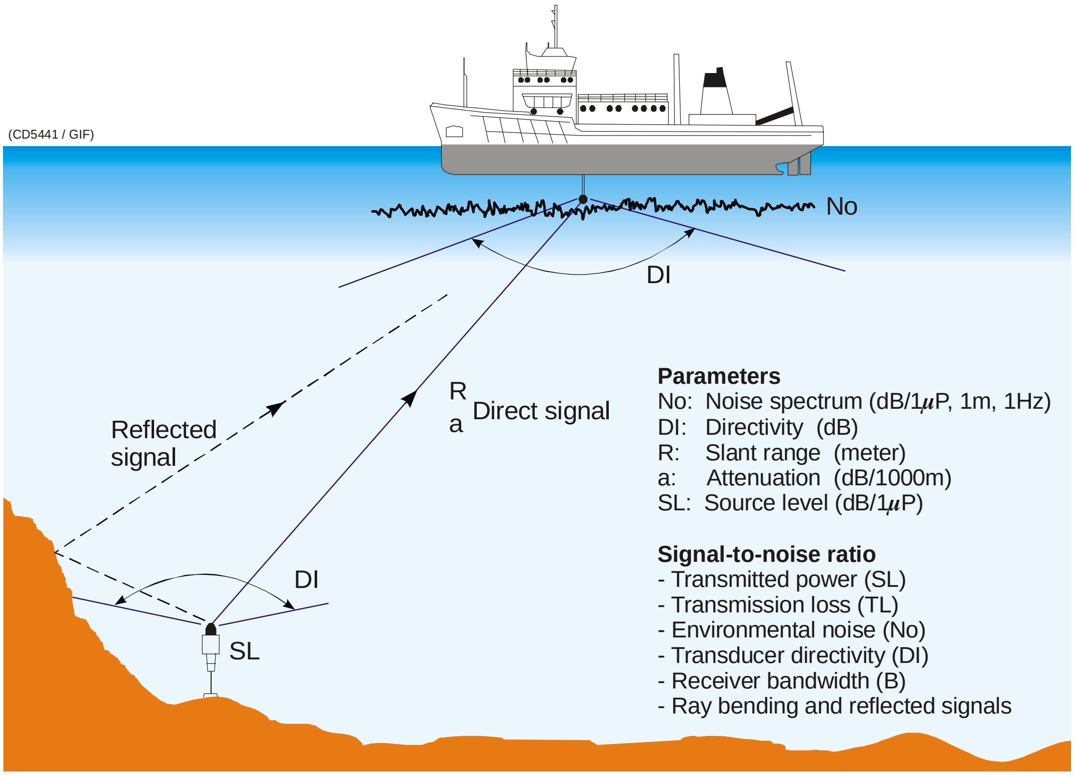
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Figure 1 - Parameters of the sonar equation

2 SOUND PROPAGATION

2.1 Pressure

A basic unit in underwater acoustics is the **pressure**, measured in μPa (micropascal) or μBar. The **Pa** is now international standard. It belongs to the MKS system, where 1μPa = 10^6 newton/m^2. The μBar belongs to the CGS system.

$$1\ \mu Bar\ =\ 10^5\ \mu Pa$$

$$0\ dB\ re\ 1\mu Bar\ =\ 100 dB\ re\ 1\mu Pa$$

The μBar is a very small unit, so negative decibels will rarely occur, if ever. To convert from μBar to μPa, simply add 100 dB.

2.2 Intensity

The sound intensity is defined as the energy passing through a unit area per second. The intensity is related to pressure by:

$$I\ =\ \frac{p^2}{\rho\ c}$$

where

I = Intensity

p = Pressure

ρ = water density

c = speed of sound in water

2.3 Decibel

The decibel is widely used in acoustic calculations. It provides a convenient way of handling large numbers and large changes i variables. It also permits quantities to be multiplied together simply by adding their decibel equivalents. The decibel notation of intensity *I* is:

$$10\ \log \frac{I}{I_o}$$

where I_0 is a reference intensity.

The decibel notation of the corresponding pressure is:

$$10\ \log \frac{p^2/\rho\ c}{p_o^2/\rho\ c}\ =\ 20\ \log \frac{p}{p_o}$$

Where p_0 is the reference pressure corresponding to I_o.

Normally p_0 is taken to 1μPa, and I_0 will then be the intensity of a plan wave with pressure 1 μPa.

Example:

A pressure $p = 100\ _{\mu}Pa$

In decibel: $20\ \log \frac{100}{1}\ =\ 40\ dB\ re\ 1\ \mu Pa$

The intensity will also be 40 dB re "the intensity of a plane wave with pressure 1_{μ}Pa".

As shown in the example, the decibel number is the same for pressure and intensity. It is therefore common practice to speak of sound level rather than pressure and intensity. The reference level is in both cases a plane wave with pressure 1 $_{\mu}$Pa.

2.4 Transmission loss

Geometrical spreading

When sound is radiated from a source and propagates in the water, it will be spread in different directions. The wave front covers a larger and larger area. For this reason the sound intensity decreases. When the distance from the source has become much larger than the source dimensions, the source can be regarded as a point source, and the wave front takes form as a part of an expanding sphere. The area increases with the square of the distance from the source, making the sound intensity decrease with the square of the distance.

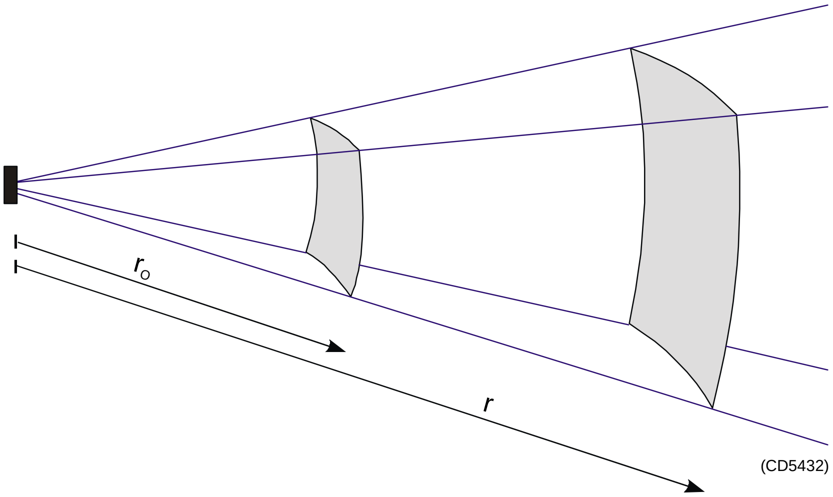


Figure 2 - Transmission loss

Let I and I_0 be the sound intensities in the distances r and r_0. Then:

$$\frac{I_o}{I} = (\frac{r}{r_o})^2$$

Expressed in decibel the geometrical spread loss is:

$$TL_1 = 10\log\frac{I_o}{I} = 20\log\frac{r}{r_o}$$

Usually a reference point is taken 1 meter in front of the source. Setting r_0 = 1 meter we get:

$$TL_1 = 20\log r$$

where r is measured in meters.

Absorbation loss

When the sound propagates through the water, part of the energy is absorbed by the water and converted to heat. For each meter a certain fraction of the energy is lost.

$$dI = -A \cdot I\,dr$$

where A is a loss factor.

This formula is a differential equation with the solution:

$$I(r) = \frac{I(r_o)}{e - Ar_o} \cdot e^{-Ar}$$

I (r_0) is the intensity at the distance r_0:

$$TL_2 = 10\log\frac{I(r_o)}{I(r)} = \alpha(r - r_o)$$

where α = 10 A log (e)

Expressed in decibel the absorption loss is proportional to the distance travelled. For each meter a certain number of decibel is lost.

If r_0 is the reference distance 1 meter, and if the ranger r is much larger than 1 meter, the absorption loss will approximately be:

$$TL_2 = \alpha r$$

α is named the absorption coefficient. Figure 11 shows absorption loss coefficient as a function of frequency. The value of α depends strongly on the frequency. It also depends on salinity, temperature and pressure.

One way transmission loss

The total transmission loss, which the sound suffers when it travels from the transducer to the target, is the sum of spreading loss and the absorption loss:

$$TL = 20\log r + \alpha r$$

where r is measured in meters, and α is measured in dB/meter.

→ *The figure on page 6 shows one way transmission loss as function of range and frequency.*

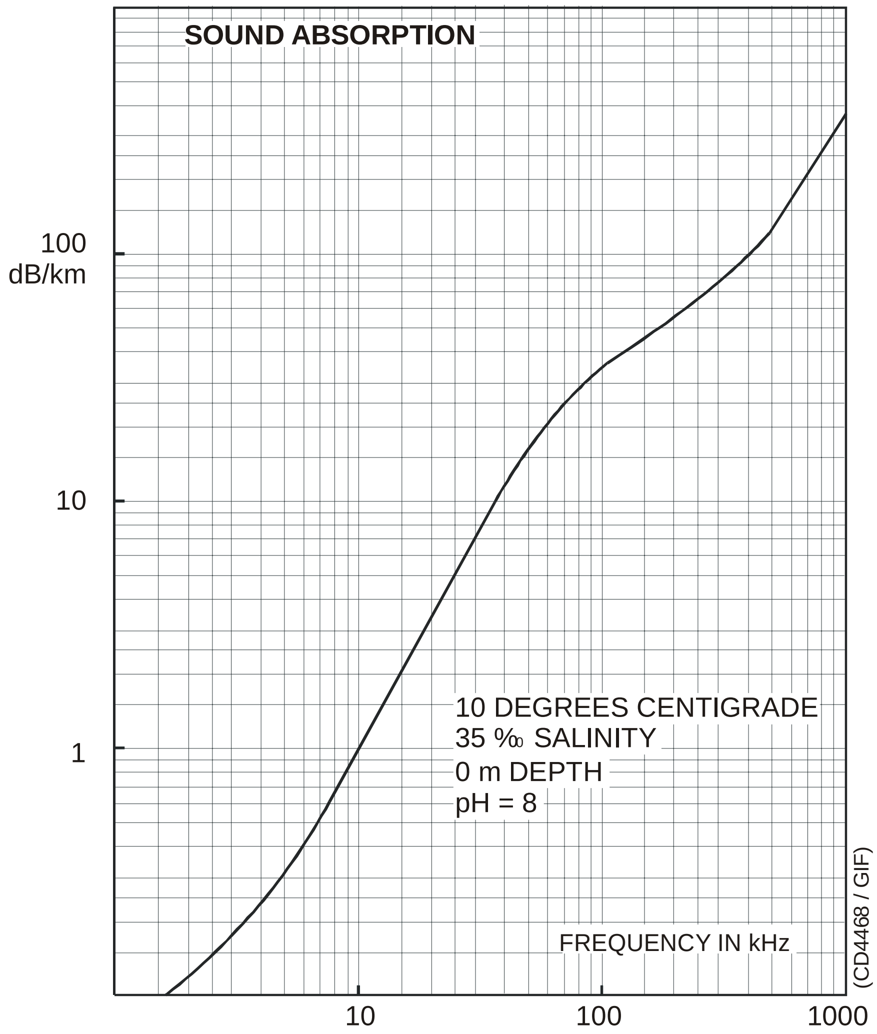


Figure 3 - Absorption loss

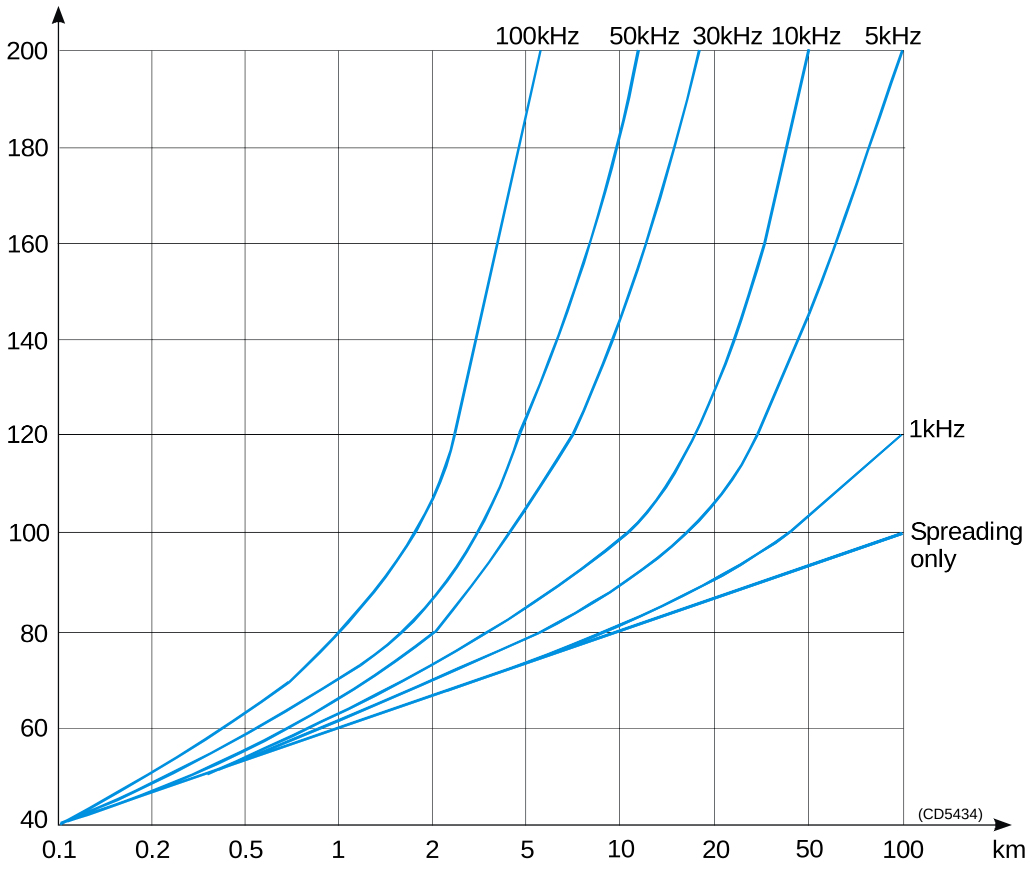


Figure 4 - Propagation loss versus range
(One way transmission loss TL = 20 log R + αR)

3 TRANSDUCERS

3.1 Construction

A modern transducer is a based on piezoelectric ceramic. The transducers may consist of an array of vibrators.

The same transducer may act as both sound source and receiver.

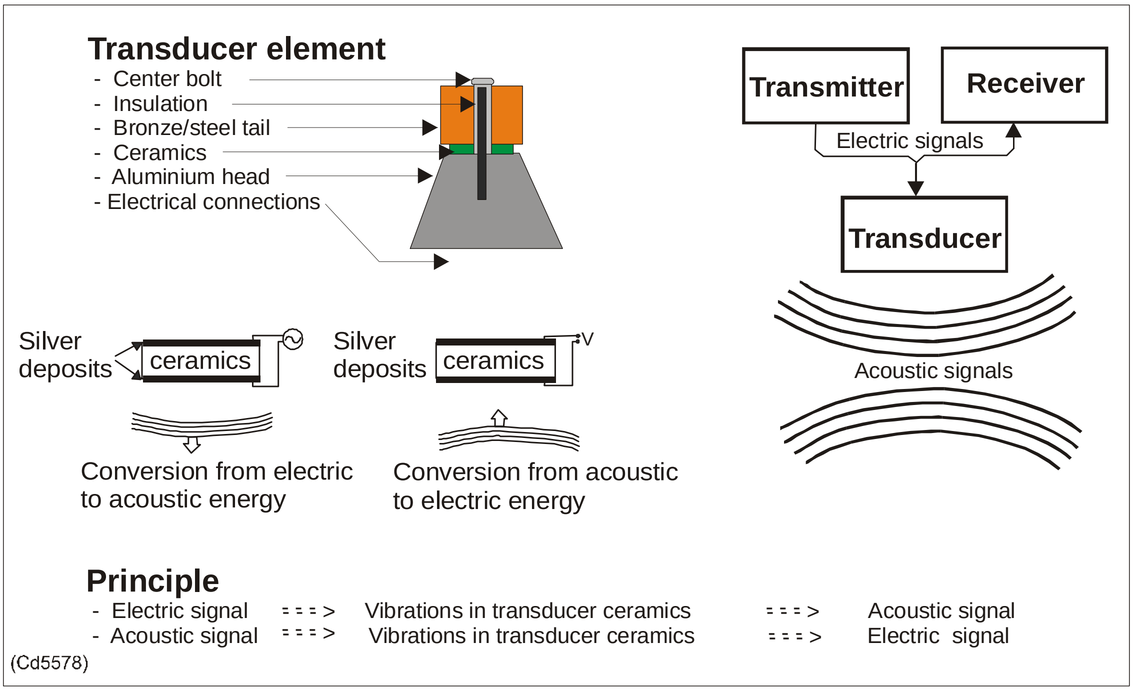


Figure 5 - Cross-section of a typical ceramic transducer

3.2 Efficiency

When the transducer converts electrical energy to sound energy or vice versa, parts of the energy is lost in friction and dielectric loss. Typical efficiency is:

- 50% for a ceramic transducer
- 25% for a nickel transducer

The efficiency is defined as the ratio of power out to power in.

3.3 Transducer bandwidth

Normal a transducer is resonant. This means that they offer maximum sensitivity at the frequency they are designed for. Outside this frequency the sensitivity drops. Typically the Q-value is between 5 and 10.

$$Q = \frac{center\ frequency}{bandwidth\ (between\ 3\ dB\ points)}$$

3.4 Beam pattern

The beam pattern shows the transducer sensitivity in different directions. It has a main lobe, normally perpendicular to the transducer face. The direction, in which the sensitivity is maximum, is called the **beam axis**. It also has unwanted side lobes and unwanted back radiation.

An important parameter is the beamwidth, defined as the angle between the two 3 dB points. As a rough rule of the thumb, the beamwidth is connected with the size of the transducer by:

$$\beta = \frac{\lambda}{L}$$

where:

β = Beamwidth in radians

λ = Wavelength

L = Linear dimension of the active transducer area (side for a rectangular area, diameter for a circular)

This rule is not valid for very small transducer i.e. $L < \lambda$.

The theoretical beam pattern of a continuous line transducer is a sinx/x function, namely:

$$b(\theta) = \left(\frac{\sin(\frac{\pi L}{\lambda} \sin\theta)}{\frac{\pi L}{\lambda} \sin\theta} \right)^2$$

where

θ = angle from the beam axis

L = line length

b = transducer power response

The figure shows this pattern in a Cartesian plot. Note that the side lobes are gradually decreasing. The first side lobe is 13 dB below the point of maximum response.

→ *Refer to figure on page 10.*

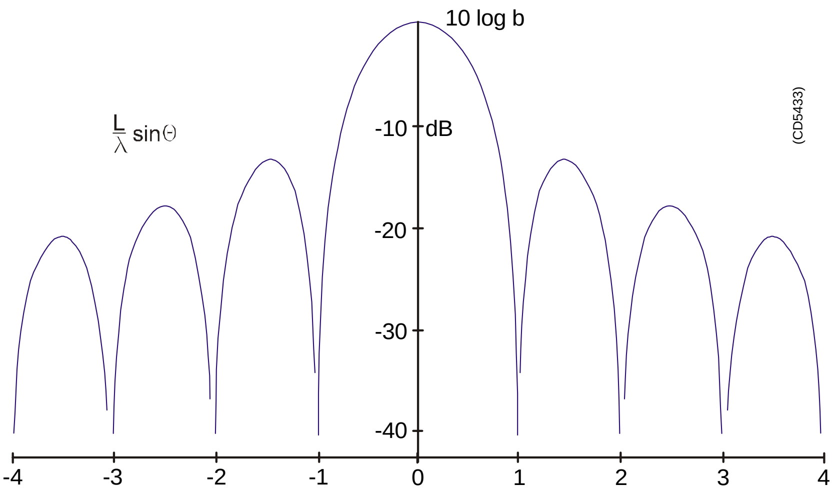


Figure 6 - Beam pattern of a continuous line

A transducer which has a rectangular active area vibrating uniformly as a piston, will have this beam pattern in the two planes parallel to the sides.

In many transducers the side lobes are reduced by a technique called tapering.

3.5 Directivity index DI

With reference to transmission, the directivity index of a transducer can be defined by:

$$DI = 10 \log \frac{I_o}{I_m}$$

where

I_o = the radiated intensity

I_m = the mean intensity for all directions (including back radiation)

Both intensities are measured in the same distance from the transducer.

The mean intensity I is equal to the intensity we would get from an omnidirectional source, if this was given the same power and had the same efficiency as the transducer. We could therefore as well define the directivity index as the ratio between the radiated intensity at the beam axis and the intensity an omnidirectional source would have given at the same point.

A transducer, which has a rectangular active area vibrating uniformly as a piston, will have this beam pattern in the two planes parallel the sides.

Examples:

Omnidirectoral source:	DI = 0 dB
Transducer with equal radiation everywhere in one halfplane and zero back radiation:	DI = 3 dB
Typical echo sounder transducer:	DI = 25 dB
Wide beam transducer:	DI = 4 dB
Medium beam transducer:	DI = 9 dB
Narrow beam transducer:	DI = 15 dB
HiPAP:	DI = 25 dB

The narrower the beam, the higher DI.

The directivity index for a transducer with beam pattern b (θ,ϕ) and the mean intensity is found by integration over all directions, with solid angle element dΩ, and division by the total solid angle 4π:

$$I_m = \frac{1}{4\pi} \int_{4\pi} I_o \cdot b(\theta\,\phi) d\,\Omega$$

According to the definition of *DI*:

$$DI = 10 \log \frac{4}{\displaystyle\int_{4\pi} b(\theta\,\phi)\ d\Omega}$$

Calculation of *DI* after this formula is, however, no easy job, not even for the simplest transducer.

If the transducer side or diameter is larger than λ the directivity index is approximately:

$$DI = 10 \log \frac{4\,\pi A}{\lambda^2}$$

where *A* is the active transducer area; $A = L^2$

When the beamwidth is known another approximate formula can be used. For a rectangular transducer the beam patterns in the two planes parallel to the sides are sinx/x function as mentioned previously.

The response is 3 dB down at:

$$\frac{L}{\lambda} \sin\theta_{3\,dB} = 0.443$$

Inserting this in the formula above gives:

$$DI = 10 \log \frac{2.47}{\sin\frac{\beta 1}{2} \sin\frac{\beta 2}{2}}$$

3.6 Transmitting response

The transmitting response of a transducer is the pressure produced at the beam axis 1 metre from the transducer by a unit electrical input. The electrical input unit may be volt, ampere or watt. A typical value for a ceramic transducer is:

S = 193 dB re 1μ Pa per watt

3.7 Source level

The source level SL of sonar or an echo sounder is the sound pressure in the transmitted pulse at the beam axis 1 meter from the transducer. If the transmitting response is known, then the source level is:

$$SL = S + 10 \log P$$

where

P =	transmitter power
S =	transmitting power response

A widely used formula is:

$$SL = 170.9 + 10 \log P + E + DI$$

where:

SL =	source level in dB re 1 $_{\mu}$Pa
P =	transmitter power in watt
E =	10 log η
η =	transducer efficiency
DI =	directivity index

The constant 170.9 incorporates conversion from watt to P_a, and can be derived as follows:

$$SL = 10 \log \frac{1}{4\pi} + 10 \log P + E + DI$$

The factor $\frac{1}{4\pi}$ represents the source level from an omni directional source, supplied with 1 watt electrical power and with 100% efficiency. When 1 watt sound power is distributed over a sphere with radius 1 meter and surface 4π meter^2 the sound intensity will be: $\frac{1}{4\pi}$ watt/m^2.

The connection between pressure and intensity is:

$$p = \sqrt{I \rho c}$$

where:

ρ =	density of water
p =	pressure

c = sound velocity

Sea water at temperature 10°C with salinity 35 $^{0}/_{00}$ at the sea surface has the following values:

ρ = 1027 kg/m

c = 1490 m/s

A sound density of 1/4 watt/m^2 will in this environment correspond to a sound pressure of:

$$p = 349 \cdot 10^{6}\,\mu Pa = 170.9\, dB\, re\, 1\,\mu Pa$$

3.8 Medium beam/Narrow beam TD

The transducers used in SSBL mode normally consists of three different groups of elements. This is to be able to calculate a three-dimensional bearing to the transponders.

- The beam width of the transducer can be changed during the operation.
    - This is achieved by combining more transducer elements in series/parallel.
- A more narrow beam gives higher directivity (higher gain and higher noise suppression from outside the beam), but will give a smaller signal ″footprint″.
- For the *Narrow beam transducer* in figure 7, the 3 dB point in wide beam mode is 160°, while in narrow beam mode the 3 dB point is 30°.
- When using the transducers in SBL or LBL mode no angle measurements are done and only the R-group (reference) is used.
    - Dedicated SBL/LBL transducers containing only one element or one group can be used.

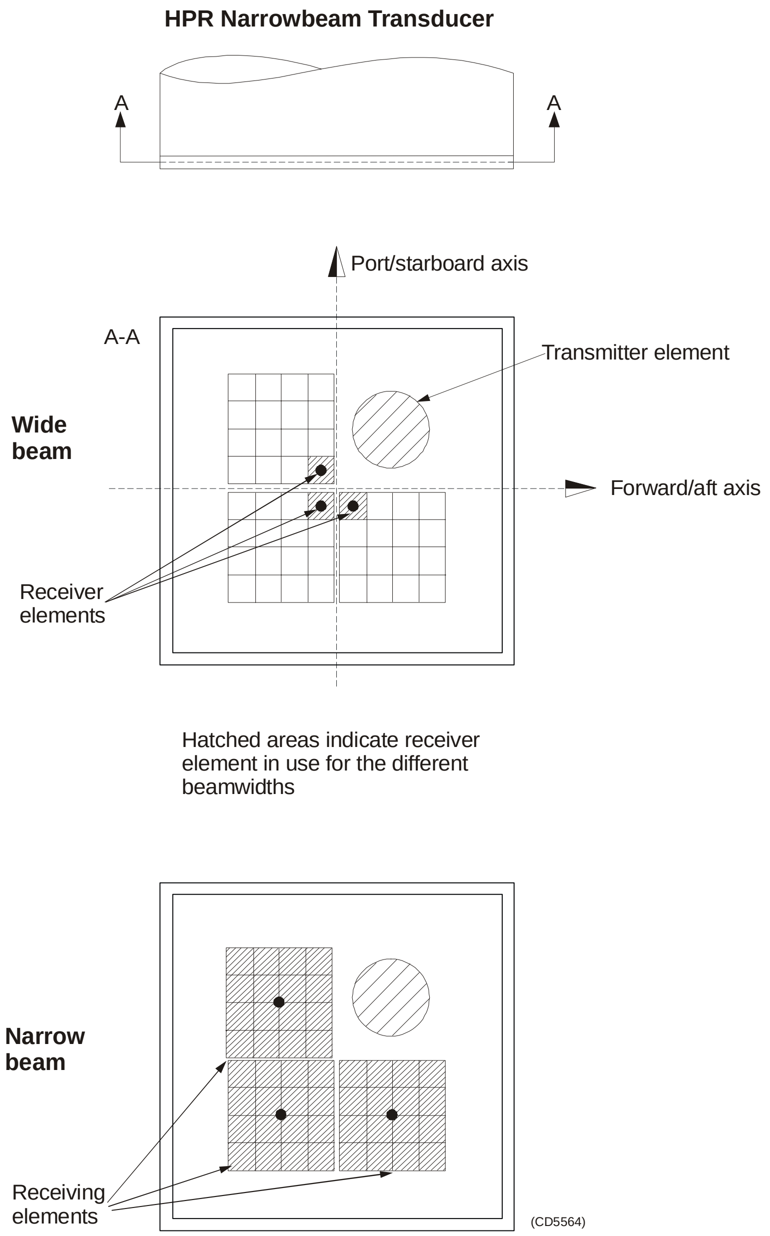


Figure 7 - Multi-element transducers

3.9 HiPAP transducer

The HiPAP transducer differs from the HPR transducers as it consists of more than 200 separate elements mounted in a sphere.

This gives the transducer a true 360° coverage from vertical to horizontal without any moving parts.

Electronic beam forming can steer narrow beams in all directions.

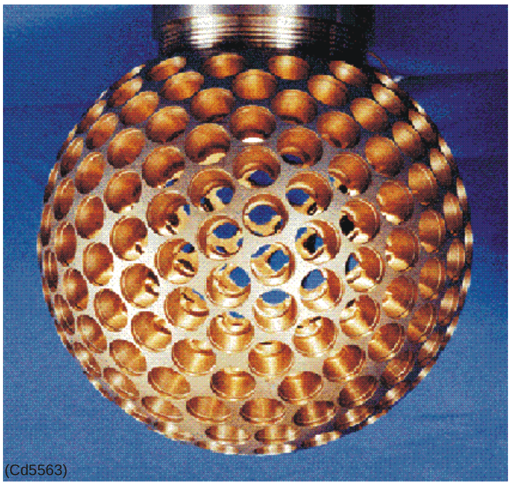


Figure 8 - HiPAP sphere

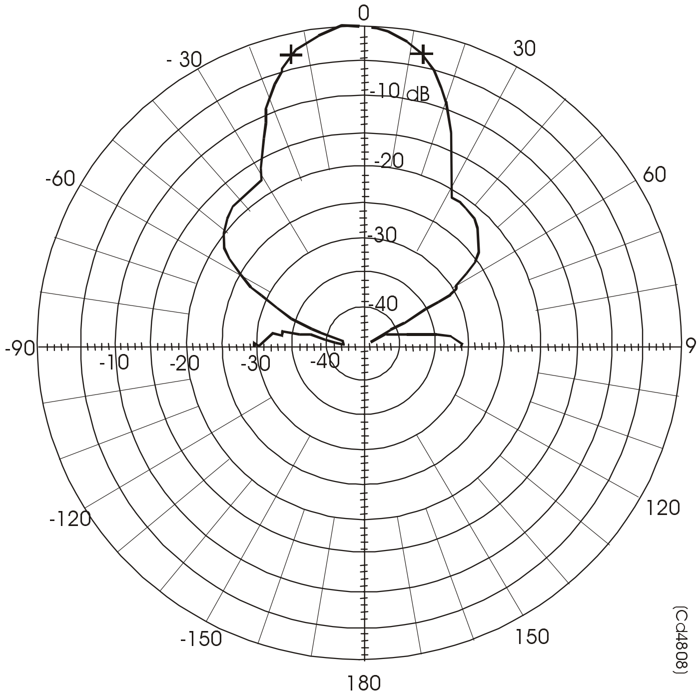
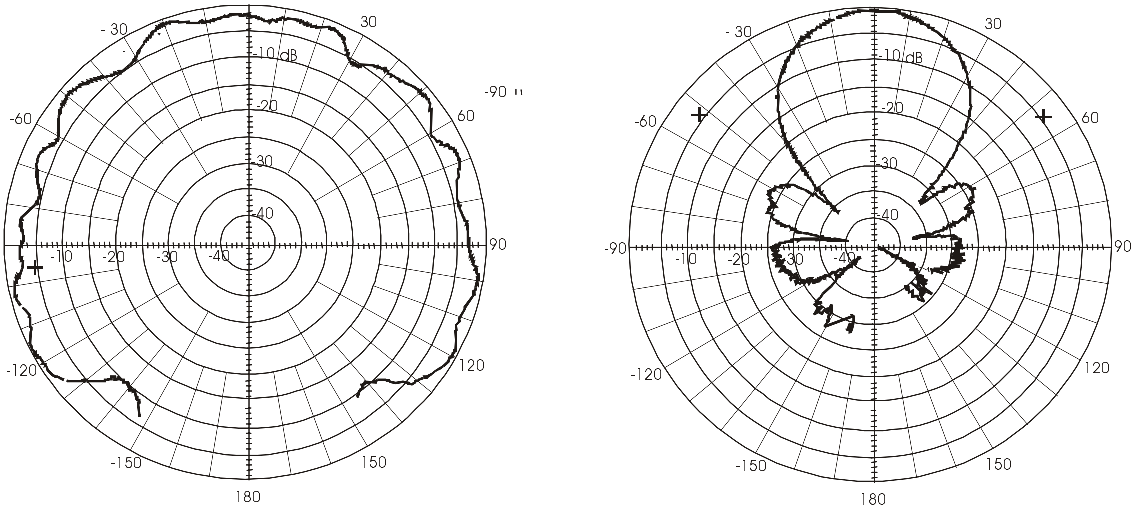
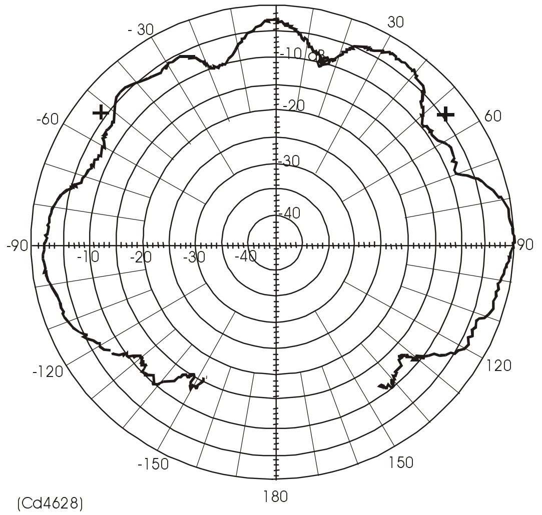


Figure 9 - Typical beam pattern for narrow beam transducer (HiPAP)



MPT 339 series
Source level = 195 dB

SPT 331 series
MPT 331/DuB vertical
Source level = 206 dB



MPT 331/DuB horizontal
Source level = 190 dB

Figure 10 - Examples of beam pattern

4 ACOUSTIC NOISE

4.1 Environmental

→ *Figure 11 shows environmental acoustic noise.*

Noise from thrusters and propellers from surface vessels is the dominating source. This noise is approximately 40 dB above normal sea noise. Common for all noise sources is that the noise level drops with approximately 10 dB per decade with increasing frequency.

4.2 Noise level at great depth

→ *The figure on page 20 shows the noise level at great depths.*

The figure shows that the noise level is very low at normal used navigation frequencies from 20 – 30 kHz.

4.3 Noise level calculation

The noise level at the system detector is calculated by the following equation:

$$N = (N_o - 10\log(B) - DI)$$

where:

B = detector bandwidth

DI = directivity of transducer

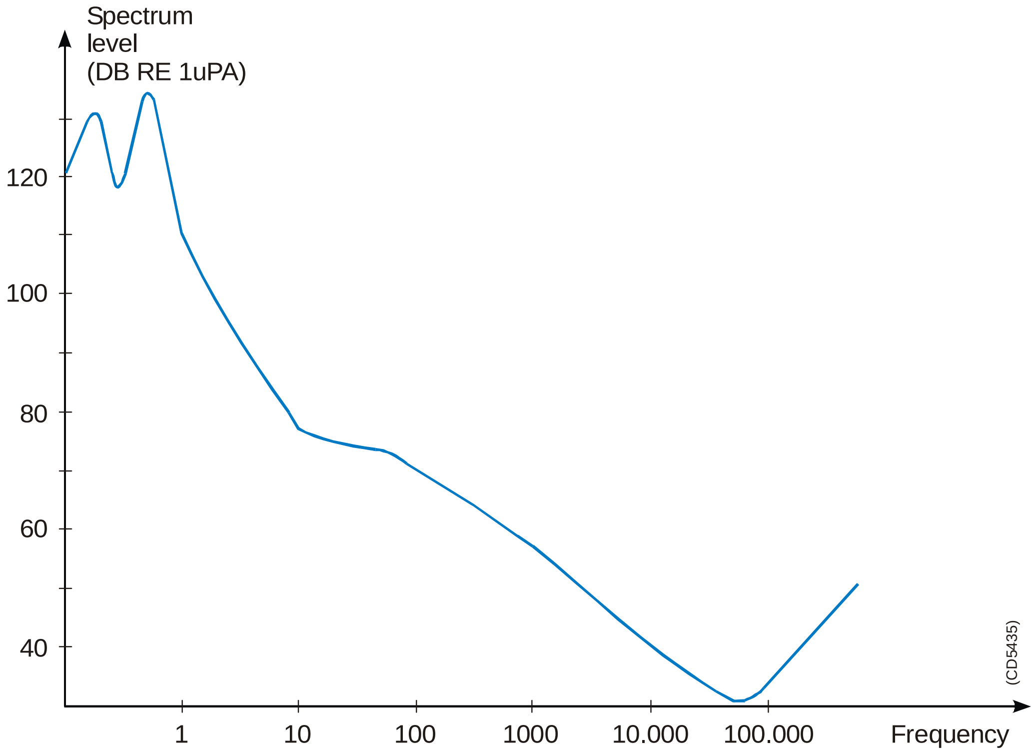


Figure 11 - Deep sea noise spectrum

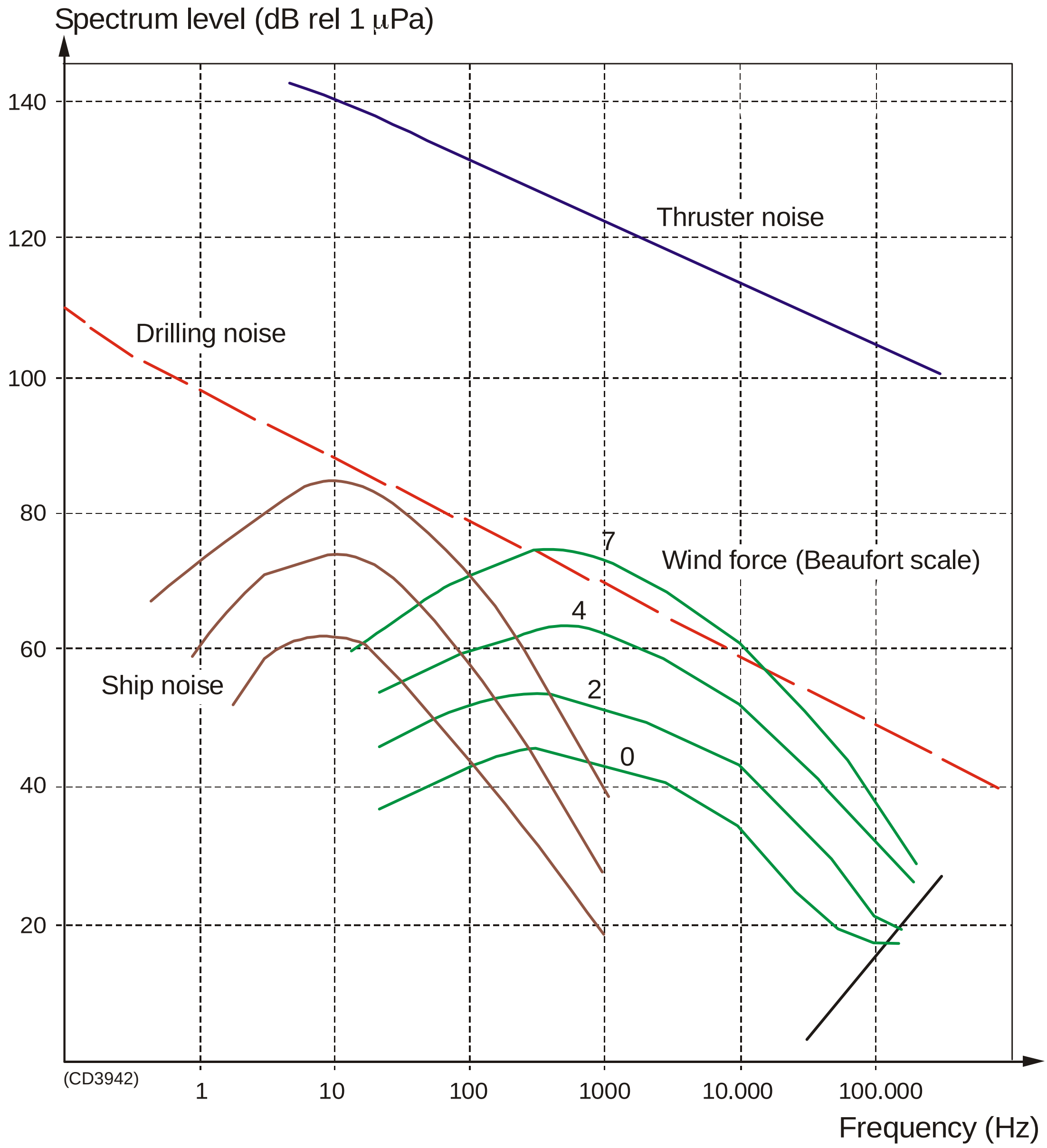


Figure 12 - Environmental acoustic noise level

4.4 Thruster noise

The noise from thruster is changing depending on the thrusters. On pitch-controlled thrusters (fixed RPM), the noise level is actually higher when running idle (0% pitch) than running with load.

→ *The curve on figure 13 shows that 100% pitch generating less noise in the 20-30 kHz area than 75% pitch.*

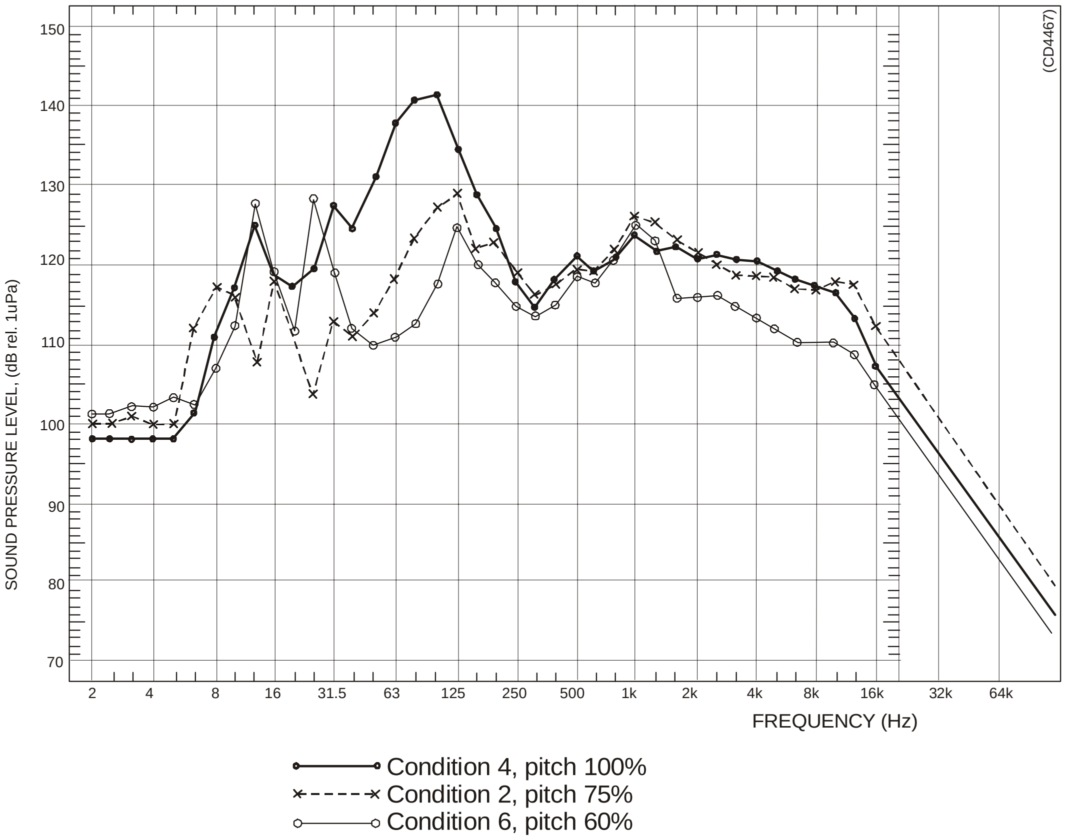


Figure 13 - Noise spectrum at different pitch levels

In addition the impact of the thruster noise is determined by the direction of the (azimuth) thruster.

Running a thruster on low RPM and high pitch generates normally less noise than a thruster on high RPM and low pitch.

In general, thrusters with variable RPM/fixed pitch generates less noise than thrusters with fixed RPM/variable pitch.

5 SOUND PATHS

5.1 General

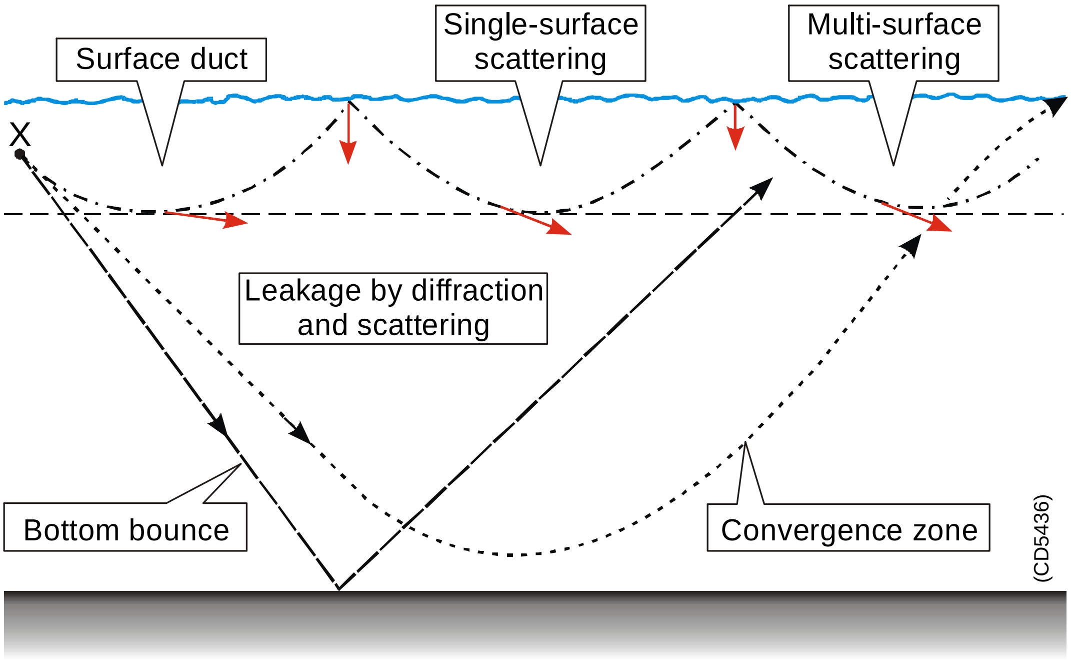


Figure 14 - Ray diagrams for deep water propagation

The velocity of sound is an increasing function of water temperature, pressure and salinity. Variations of these parameters produce velocity changes, which in turn causes a sound wave to refract or change its direction of propagation. If the velocity gradient increases the ray curvature is concave upwards. If the velocity gradient is negative, the ray curvature is concave downwards.

→ *Figure 14 illustrates sound transmission for a near surface source and for a deep-water source.*

The refraction of the sound paths represents the major limitations to a reliable underwater navigation and telemetry system. The multipath conditions can vary significantly depending on ocean depth, type of bottom and transducer-transducer configuration and their respective beam patterns.

The multipath transmissions result in a time and frequency smearing of the received signal as illustrated.

→ *Refer to figure on page 27.*

There are several ways of attacking this problem. The obvious solution is to eliminate the multiple arrivals by combining careful signal detection design and the use of directional transducer beam. Directional receiving beam discriminates against energy outside of the arrival direction and directional transmit beam project the energy, so that a minimum number of propagation paths are excited.

5.2 Sound velocity and ray bending

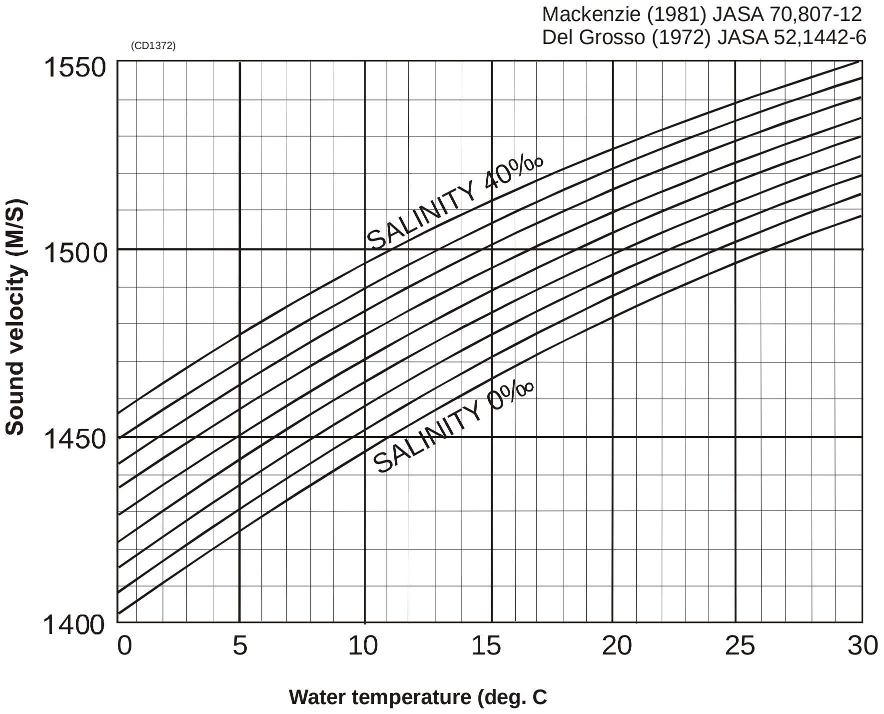


Figure 15 - Example of velocity change with changing temperature and salinity

Figure 15 shows the velocity is changing with changing temperature and salinity. In addition, the velocity is increasing with increasing depth (approximately 0.017 m/s per meter).

The sound path with varying velocity can be simulated and displayed.

→ *Refer to figure on page 24.*

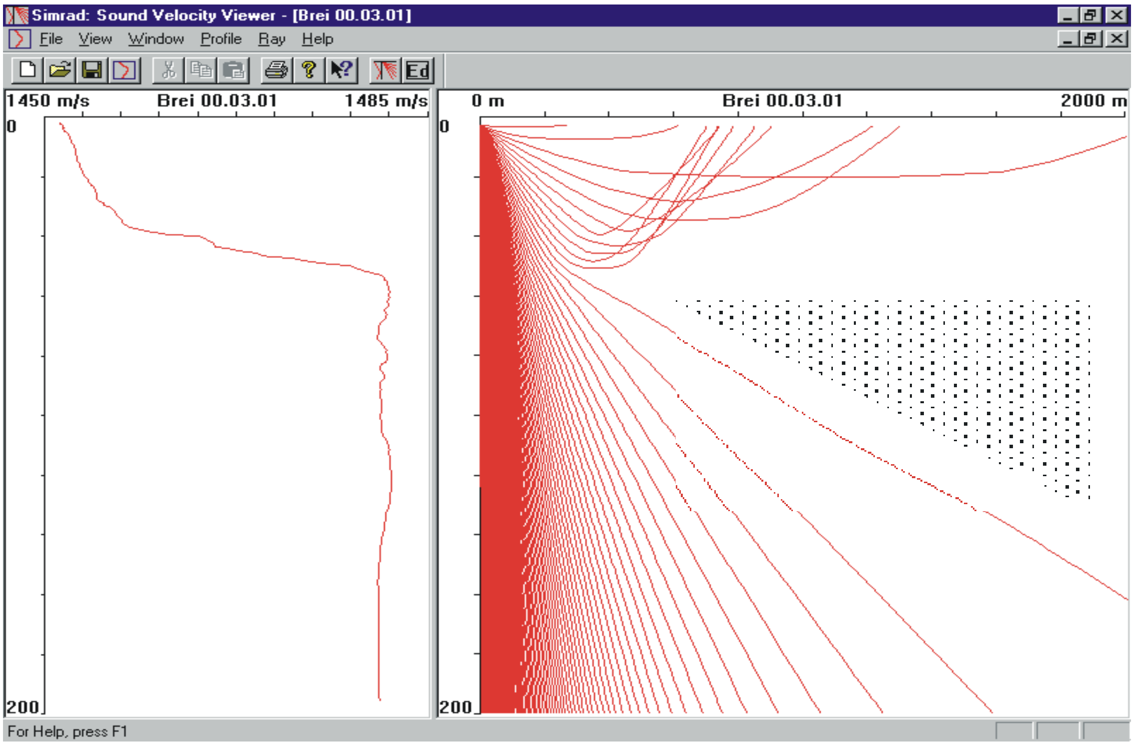


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Figure 16 - Example of sound velocity

The shaded area of the figure illustrates an area where you can not expect to have any coverage by the acoustic system due to the ray bending.

5.3 Reflections

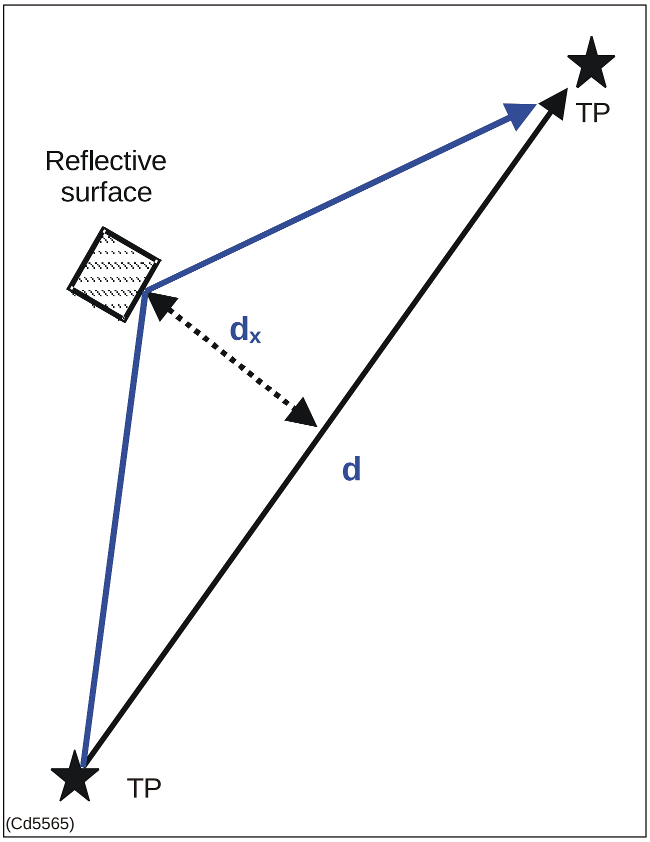

Figure 17 - Two LBL transponders measuring baseline

→ *The example in figure 17 shows two LBL transponders measuring baselines.*

Reflections can be caused when the signal bounces off a subsea structure, seabed, raiser, ships hull or surface.

Normally the reflection is not perfect, meaning the reflected pulse have less energy than the direct pulse and should not cause problems. Sometimes the pulse is so strong it might cause problems for the pulse detection in the receiver.

When two pulses (sine waves) are added, the resultant can be stronger or weaker than a single pulse. Adding two signals that are 180° out of phase and of equal strength will create no signal at all.

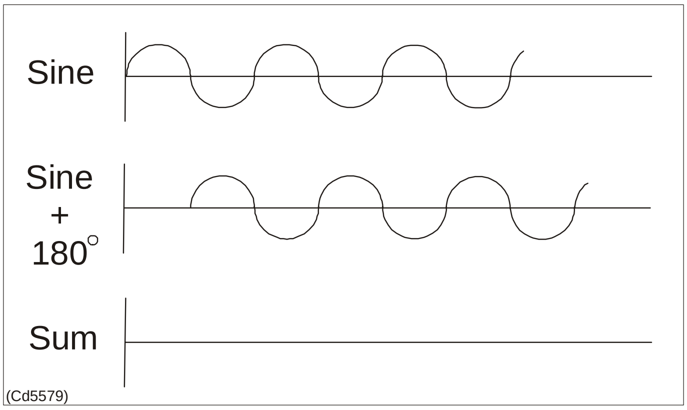

Figure 18 - Sine waves

If the signal path of the reflection is 0.5λ (or multiples of this) longer, the above situation might occur.

Example (refer to the figure above):

f = 30 kHz $\Rightarrow$ $\lambda = 0.05$ m
d = 100 m

180° phase shift ($1/2\lambda$):
$dx = \surd((100.025/2)2-(100/2)^2) = 1.12$ m

180° phase shift ($2+1/2\lambda$):
$dx = \surd((100.125/2)2-(100/2)^2) = 2.50$ m

This shows that a surface with 100% reflection will create no resulting signal at the receiver given the distances.

The same problem can be caused by ray bending or reflections from raisers or ship's hull.

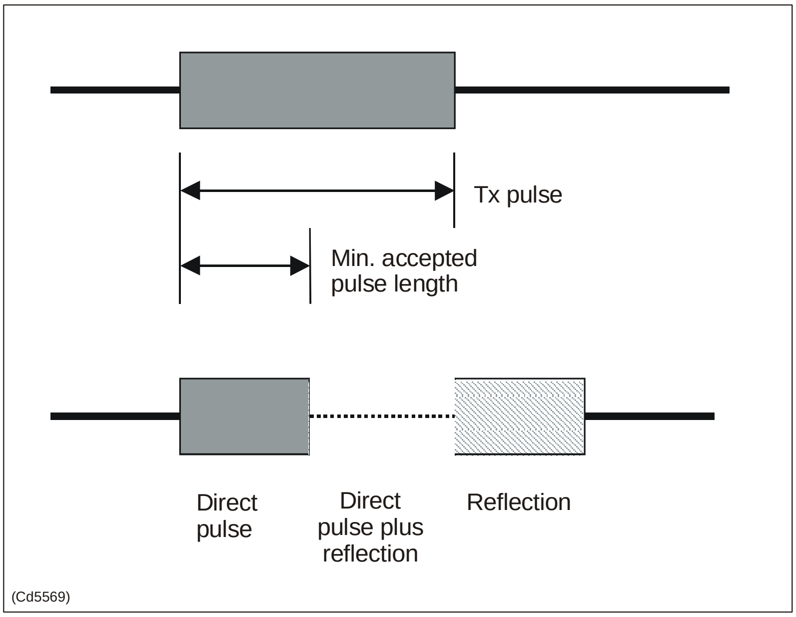

Figure 19 - Received pulse

Even reflections that are much delayed might cause problems. The receiver has certain criteria to accept the signal as a pulse. One of them is the pulse length. As the figure above illustrates, a worst case condition will be that the direct pulse length is too short to be acknowledged as a pulse before the reflection cancels it. Then the remainder of the reflection is just long enough to be accepted as a pulse.

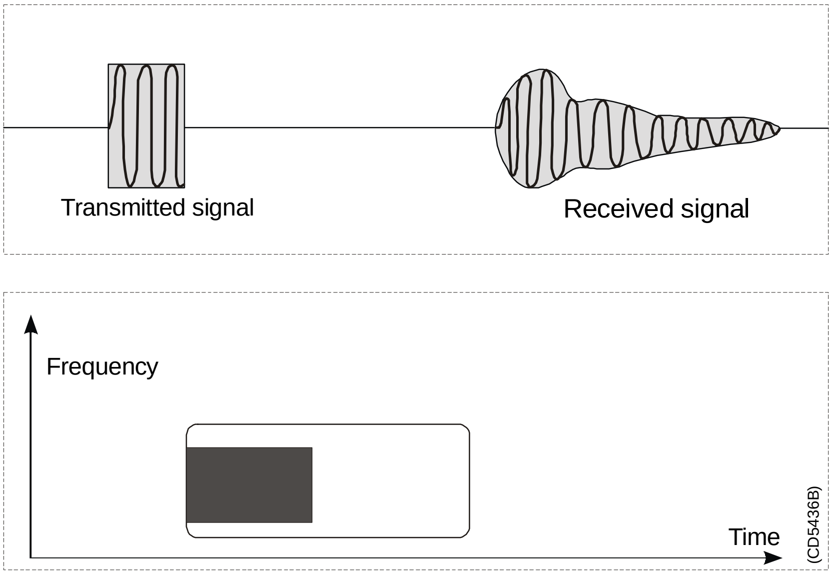

Figure 20 - Multipath transmission: time and frequency smearing of acoustic signals

6 POSITIONING PRINCIPLES

6.1 General

There are three different main positioning principles in use. In addition you can have a combination of the three. These are:

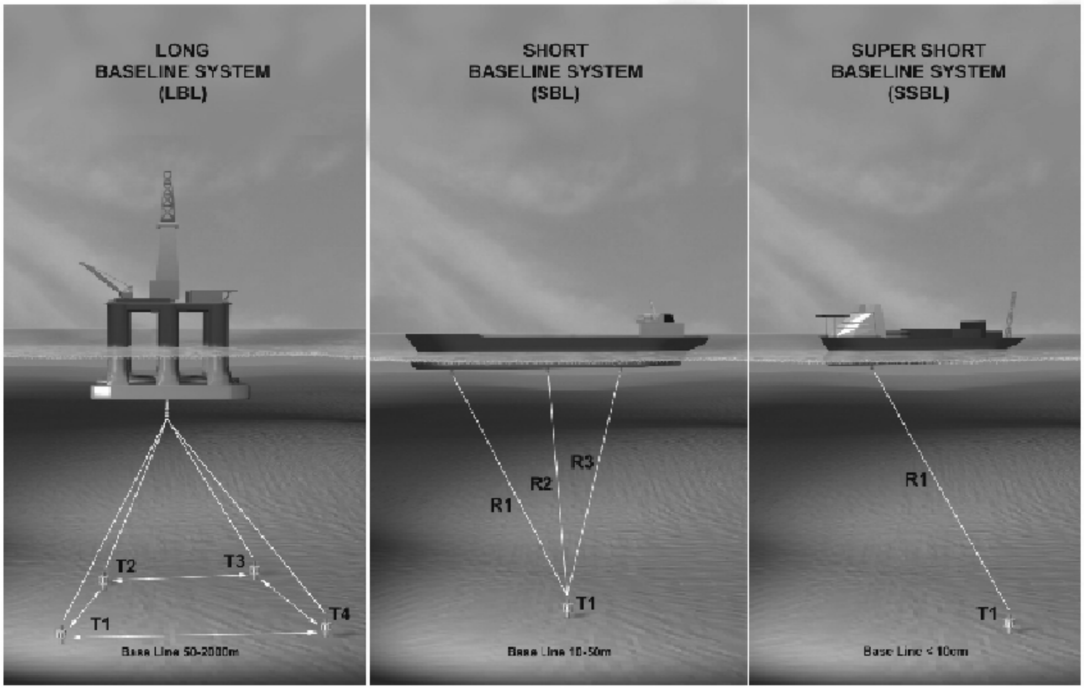

Figure 21 - Positioning principles

- **LBL, Long Base Line**
    - Long base line (LBL) refers to the distances between the transponders on the seabed. The distances can be from a few meters up to 2000m+. The ship's transducer(s) might consist of only one group of elements. The system requires at least 3 transponders to be able to calculate a position fix (the same principle as GPS systems).
- **SSBL, Super Short Base Line**
    - Super short base line (SSBL) reflects the distance (base line) between the receiving elements in the transducer (2-8 cm). Compared to the distances of SBL/LBL (10-2000 m) this is super short! The phase differences between the signals at these elements are used to calculate a transponder position that can be 2000-3000 m away.

- **SBL, Short Base Line**
    - Short base line (SBL) refers to the distance between the transducers installed on the vessel. These distances can be 10-50 m depending on the hull, and compared to the LBL system these ranges are short. The SBL systems use one transponder at the time.

6.2 LBL

All transponders (3 or more) in the LBL array have to be in known positions. These can be in a local grid or in geographic co-ordinates. The positions can be computed by measuring the individual base lines between the transponders during. This is also called ″local calibration″.

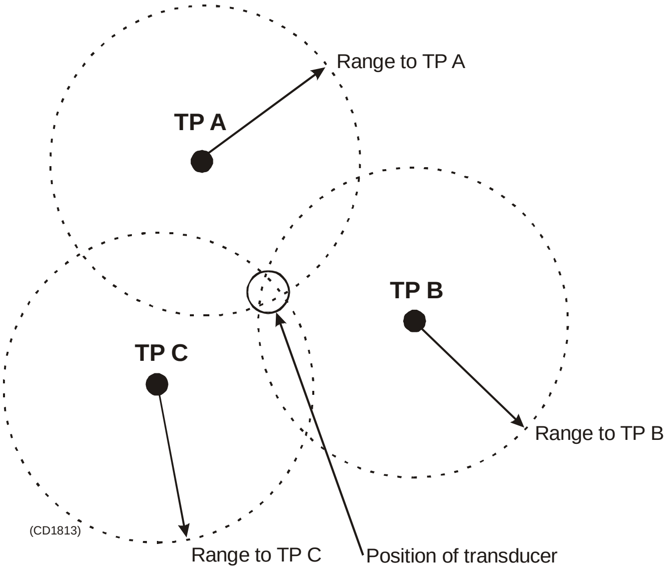

Figure 22 - LBL array

To determine the position of the transducer being positioned, all transponders are interrogated using a common interrogation channel and the range to each transponder is calculated and entered in an ″least squares″ algorithm.

The transducer being positioned in LBL mode can be on a surface vessel, subsea vehicle or a mobile transponder.

The update rate for a LBL system is slower than SSBL/SBL systems because the replies from the have to come in sequence. Typical update rates are 2-4 seconds depending on the water depth, number of transponders, base lines of the array and position of the transducer (vessel) in relation to the array.

6.3 SSBL

The SSBL systems are interrogating one transponder at the time. The reply is from the transponder is picked up by the transducer. The phase difference between the three groups of elements inside the transducer is used to calculate the bearing to the transponder.

The time from the interrogation to the reply is received is used to calculate the distance to the transponder.

By combining the bearing and distance to the transponder, an X-Y-Z position is calculated.

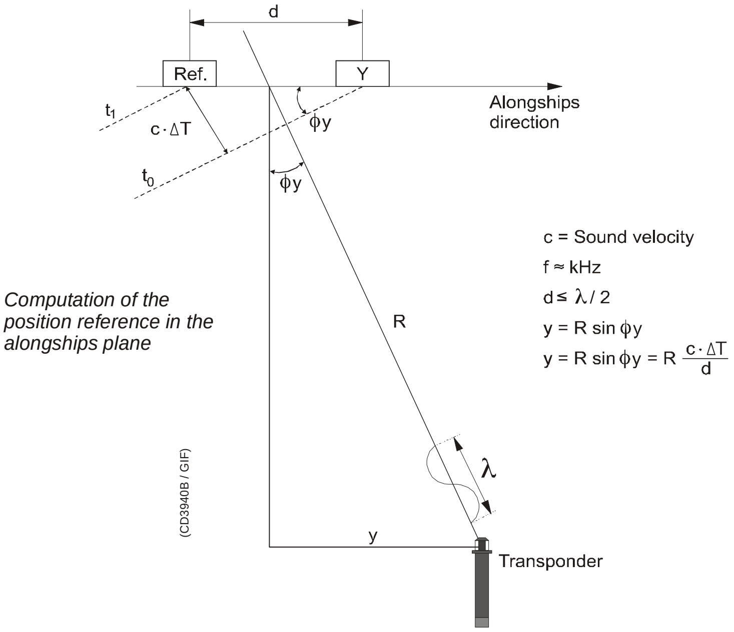

Figure 23 - SSBL principles

6.4 SBL

The SBL systems work as a SSBL system by interrogating one transponder at the time. Instead of having the X, Y and R elements inside one transducer these are separate transducers installed 10-50 m apart.

In theory the system works as a LBL system turned upside-down.

6.5 Combination of systems

A LBL or SSBL system with 3 active transducers can use the received information to calculate SBL position/an integrated position as well.

7 EXAMPLE

7.1 General

This chapter contains an example of evaluation of a narrow beam navigation system working in high noise multipath environments, using the sonar equation.

7.2 The Sea as the transmission medium

The sea is far from an ideal transmission medium. Acoustic noise and multipath interference is the major concern. It limits the accuracy and range of the system. Acoustic noise generated by propeller/thrusters and from drilling activities dominates the acoustic noise picture. Variation in the vertical velocity gradient causes the sound path to be refracted causing multipath transmission to occur.

The use of a narrow beam to reduce the noise and multipath problems is obvious for two reasons:

1. Narrow beam receiving will reduce the influence of noise from noise sources outside the beam and discriminate against multipath signals arriving outside the beam.
2. Narrow beam transmitting will concentrate the signal energy so that a minimum number of possible propagation paths are excited.

The advantage of narrow beam receiving and transmitting will increase the performance of the navigation system in three ways:

1. Increased range
2. Reduced power requirements
3. Increased accuracy

7.3 Theoretical evaluation

Reliable signal detection and accurate position measurement require an acoustic signal level that is well above the acoustic noise level. The different parameters that defines the S/N-ration is described by the **sonar equation**:

[1] $$(S/N) = SL + DI_t - 20\log(R) - \alpha \cdot R - (N_o + 10\log(B) - DI_r)$$

where:

SL = Source level of transmitted signal

DT_t = directivity of transducer in transmit mode

20log(R) = spreading of acoustic signal as a function of range (R)

$\alpha \cdot R$ = attenuation of acoustic signal as a function of damping (α) and range (R)

N_o = acoustic noise level from propeller/thrusters and sea background noise

10log (B) = bandwidth of receiver

DI_r = directivity of transducer in receive mode

R = range in m

Example:

SL = 188 dB rel 1μPa at 1 m

α = 7dB/km (at 30 kHz)

B = 200 Hz

N_o = 80dB rel 1μPascal pr. Hz (drill noise)

(S/N) = 20dB requirements (in detector)

$DI_t = DI_r$ = 4 dB wide beam system

$DI_t = DI_r$ = 17 dB narrow beam system

Maximum range of the wide beam system:

$$\begin{aligned}
&(S/N)_w \\
&\quad = SL + DI_t - 20\log(R) - \alpha \cdot R - (N_o + 10\log(B) - DI_r) \\
&\quad = 20\,dB \\
&\quad = 188 + 4 - 20\log(1400) - \frac{7 \cdot 1400}{1000} - (80 + 10\log(200) - 4) \\
&\quad = 20\,dB
\end{aligned}$$

this gives as a result: $R_{\max} = 1400\,meters$

The corresponding (S/N) ratio of a narrow beam system is:

$$\begin{aligned}
&(S/N) \\
&\quad = 188 + 17 - 20\log(1400) - \frac{7 \cdot 1400}{1000} - (80 + 10\log(200) - 17) \\
&\quad = 46\,dB
\end{aligned}$$

The difference in (S/N) ratio of 26 dB between the wide and the narrow beam system corresponds to the difference in directivity of the two systems.

The increased (S/N)-ratio can be used either to increase the range, reduce the power requirements or to reduce the variance on the position measurements:

Increased rage

$$\begin{aligned}
&(S/N)_n \\
&\quad = 188 + 17 - 20\log(R) - \alpha \cdot R - (80 + 10\log(200) - 17 \;\; 20\,dB)
\end{aligned}$$

$R_{\max} = 3800\,meters$

7.4 Reduced power requirements

The increase in (S/N)-ratio can alternatively be used to reduce the power requirements, increasing the lifetime or reducing the volume of a subsea battery powered system.

The increase in (S/N)-ratio of 26 dB corresponds to an increased lifetime or a reduced battery volume with a factor of 400.

Reduced position measurement variance

The measurement principle is illustrated below.

→ *Refer to figure 24 on page 34.*

Increased (S/N)-ratio will reduce the variance of the position measurements according to the following.

Position:

$$x = R \cdot \sin\theta_x = R\frac{c}{d} \cdot \Delta T \tag{1}$$

Position variance:

$$\sigma_x{}^2 = \left(\frac{c}{d}\Delta T\right)^2 (\sigma_r)^2 + \left(R\frac{c}{d}\right)^2 \cdot (\sigma \Delta T)^2 \tag{2}$$

where:

$$\sigma_r = \frac{c}{B(2\,S/N)^{1/2}} \tag{3}$$

$$\Delta T = \frac{T}{2\,\pi\,(S/N)^{1/2}} \tag{4}$$

where

c = sound velocity

T = time period of transponder pulse carrier frequency

B = bandwidth of detector

d = baseline length between transducer phase measurement groups

ΔT = phase/time difference

λ = C T = wave length of transponder pulse carrier frequency

$$\lambda = \frac{c}{f} = \frac{c}{\frac{1}{T}} = CT$$

Inserting (3) and (4) in (2) and observe the last element in (2) is dominating gives:

$$\sigma_x = R \cdot \frac{c \cdot T}{2\,\pi d \cdot (S/N)^{1/2}} = R \cdot \frac{\frac{\lambda}{d}}{2\pi \cdot (S/N)^{1/2}} \text{ (meter)}$$

Variance in % of slant range:

$$\sigma_x = \frac{\frac{\lambda}{d}}{2\pi \cdot (S/N)^{1/2}} \cdot 100\ (\%)$$

Example:

$R = 1400\,m$

$(S/N)_{wide} = 20\,dB$

$(S/N)_{narrow} = 46\,dB$

$d_{narrow} = 4\,d$

$(\sigma)_{x\ wide} = 3.2\ (\%\ \text{of R})$

$(\sigma)_{x\ narrow} = 0.4\ (\%\ \text{of R})$

The variance of the narrow beam system is reduced with a factor of 8 compared to the wide beam system.

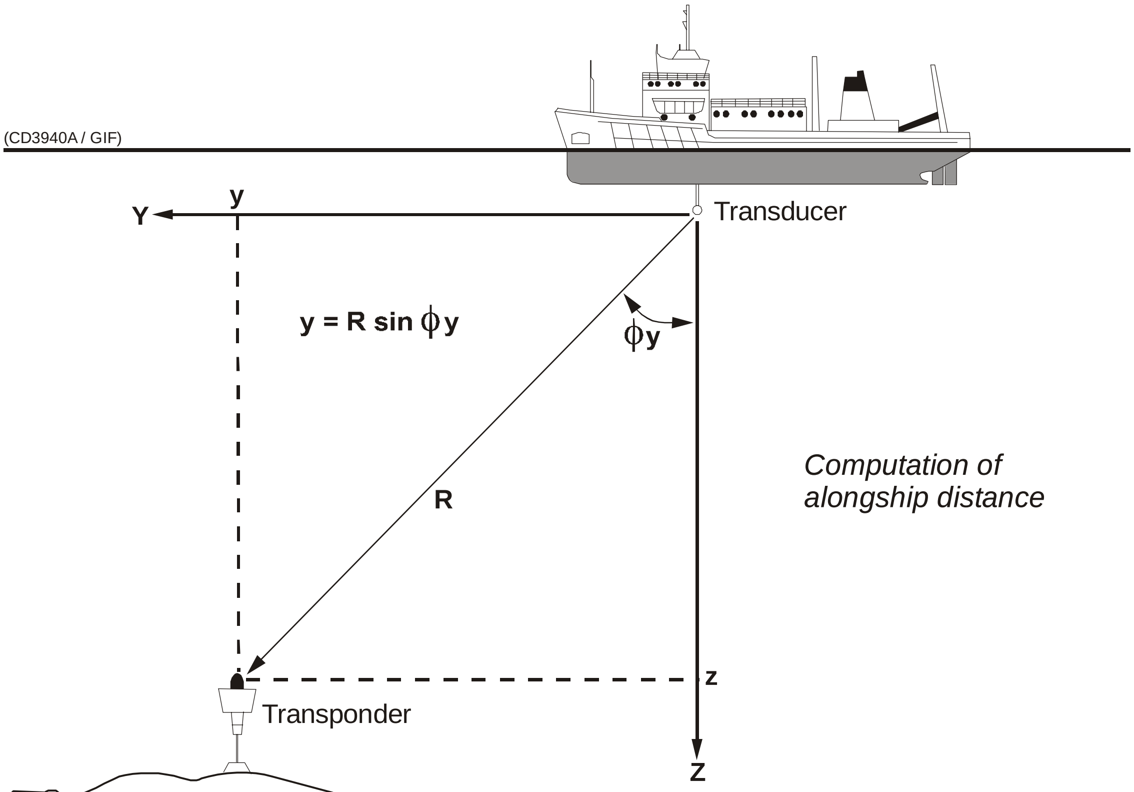

Figure 24 - HPR measurement principle: Computation of alongship distance

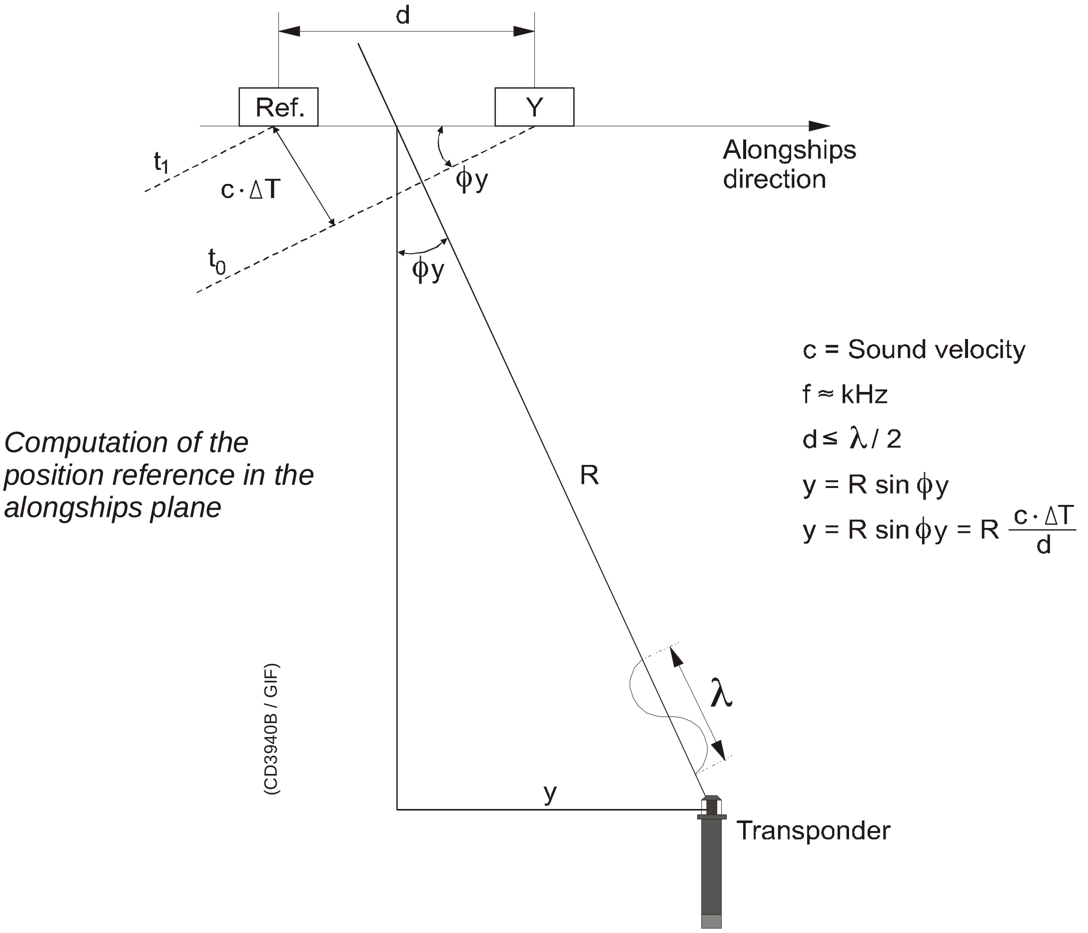

Figure 25 - HPR measurement principle:
Computation of the position reference in the alongship plane

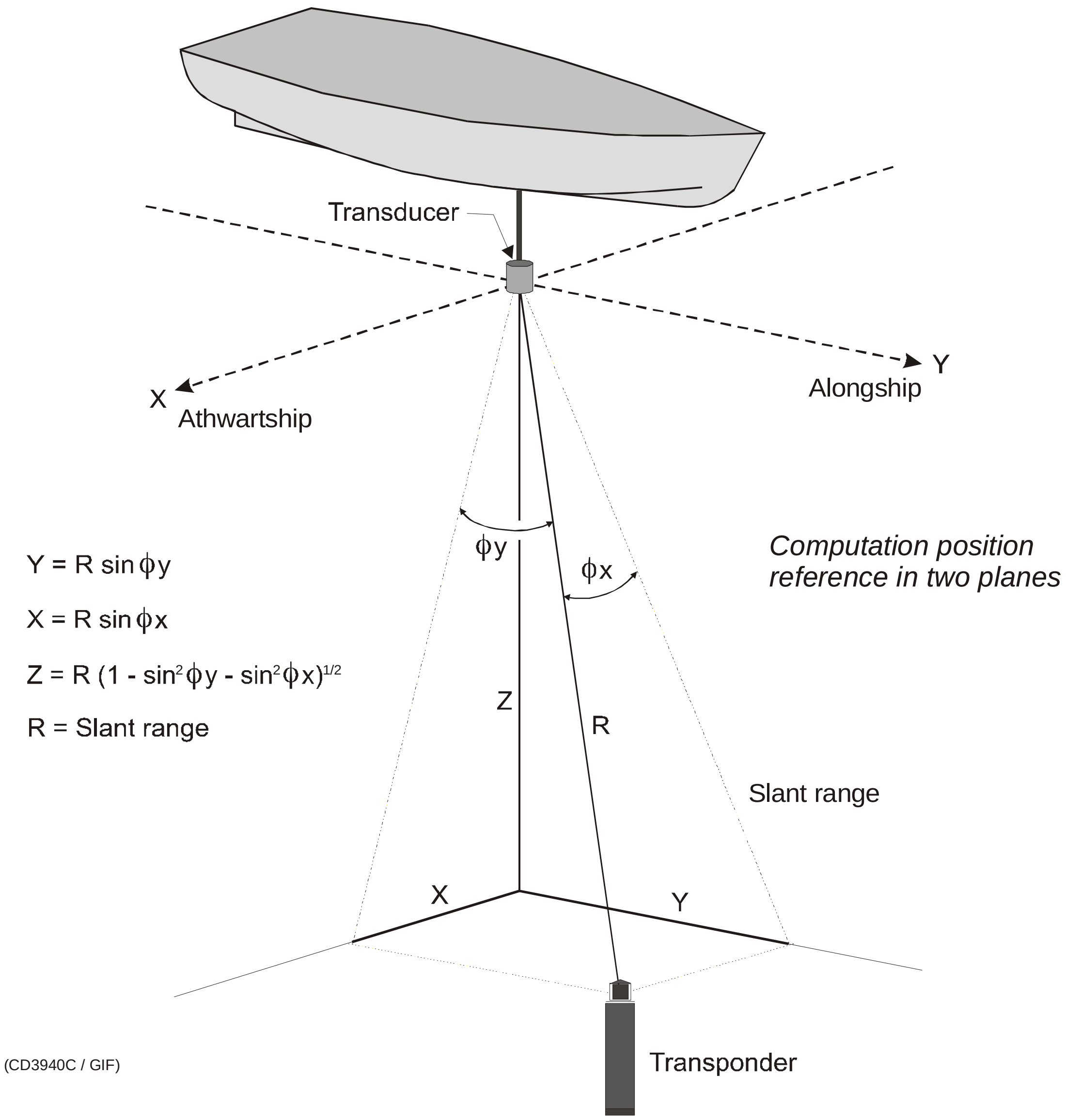

Figure 26 - HPR measurement principle: Computation position reference in two planes

8 PERFORMANCE OF ACOUSTIC POSITIONING SYSTEMS

8.1 Introduction

Underwater navigation systems using hydro-acoustic principles have been used for more than 20 years. As underwater positioning in general takes place in increasing water depths, the requirements for the systems increases.

To meet this challenge, the systems have been continuously improved through the years, and it has become more and more important also to focus on "outside" factors that influences the performance.

The requested performance for dynamic positioning application is normally related to *repeatability* and system quality factors like *MTBF, Availability and Integrity.* Regarding accuracy, other applications like survey, module installation, pipe laying etc. focuses on *absolute accuracy*, that means the position accuracy of a fixed transponder (i.e. at the sea floor) compared to global co-ordinates.

To minimize confusion we have therefore included performance figures for *absolute accuracy* for LBL, SSBL and HiPAP.

The following refers to systems in the MF Band (27 - 32 kHz).

8.2 Super short base line (SSBL) systems

SSBL and HiPAP systems measures the angle and the distance to one or more transponders at the sea floor and then calculates the resulting position. The accuracy of the SSBL and HiPAP systems is therefore directly dependant the slant range as the systems measures angles. In addition, the accuracy is dependant the signal-to-noise (S/N) ratio, at the receiving transducer.

The position accuracy is expressed in degrees or as "%" of the distance (slant range) between the transponder and the transducer at the ship. The position accuracy is stated with a standard deviation of "one Sigma". (Which means that 67% of the measurements are within the stated result.)

The formula to calculate the standard deviation in one plane for a SSBL system is called Cramer -Rao and follows:

$$\sigma_{CR} = \frac{\phi}{2}\sqrt{\frac{1 + SN_{Bm}}{SN^2{}_{Bm}}}$$

The total position standard deviation is:

$$\sigma = \sqrt{\frac{\pi}{2}}$$

Where:

δ =. Standard deviation (in degrees)

ϕ = Transducer opening angle (in degrees)

SN_{Bm} = Signal-to-noise power ratio in a beam

The transducer elements are in most cases not perfect. They will be burdened with a phase standard deviation.

In the following diagram, the **solid** lines has taken this variance into account and the angular variance is set to 7 electrical degrees. For the **dotted** lines this error is set to zero.

→ *Refer to figure 27.*

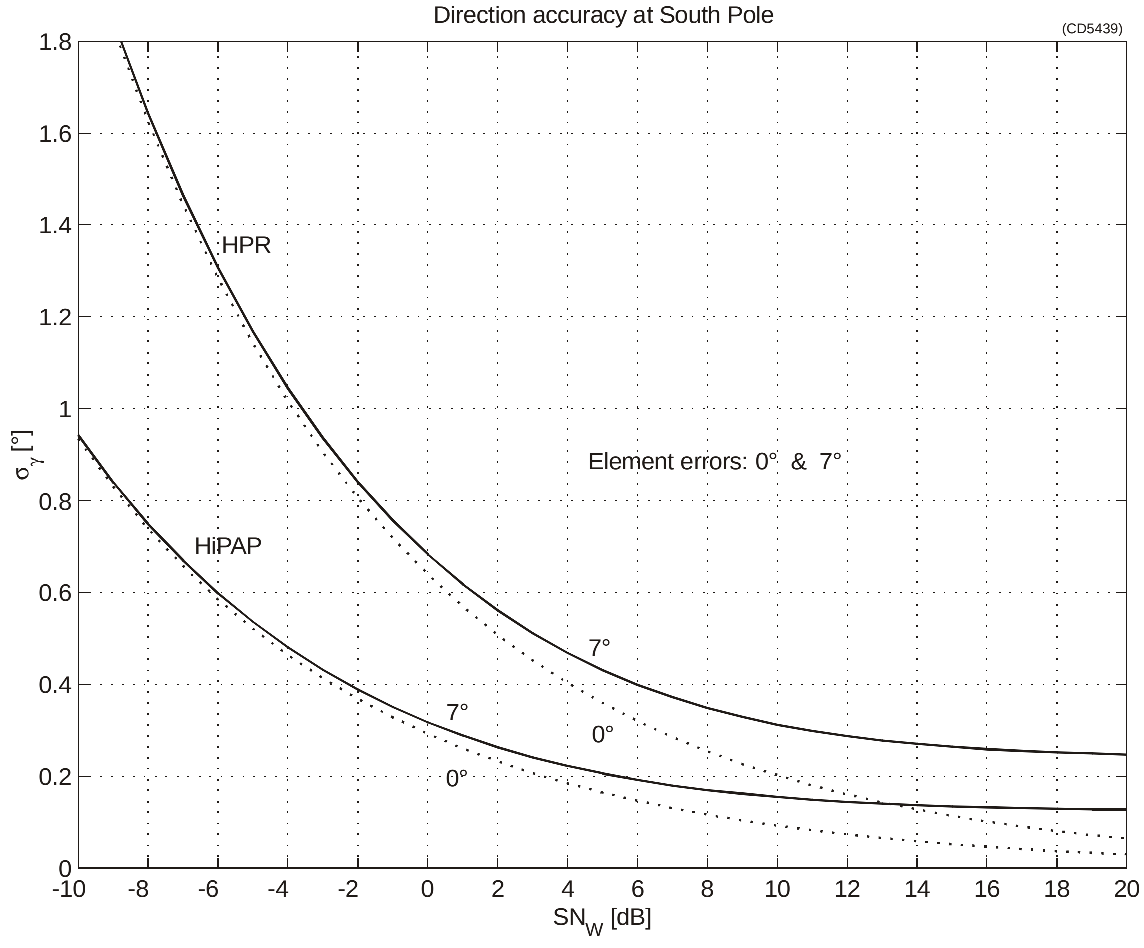

Figure 27 - Absolute accuracy of the SSBL NB / HiPAP systems

The relation between S/N in water and S/N in a beam expressed in dB is as follows:

$$S/N_w = S/N_{Bm} - DI$$

Where *DI* is the directivity index of the transducer.

It is assumed that all external errors (from vertical reference units, installation parameter, offsets, surface navigation etc.) are removed. In practice, these errors are minimised by field calibration following separate procedures.

Compensation for change in sound velocity should always be done if absolute positioning is required. To measure sound velocity, a probe to deploy may be used. In some cases it may be sufficient to put "fixed depth" into the system if the actual depth is known.

However, the position repeatability is not influenced by variations in sound velocity.

8.3 Long base line (LBL) systems

LBL systems measures the distances between the receiving transducer at the ship, and the transponders in a transponder array at the bottom. The transponder array must be pre-calibrated, that means all distances between the transponders as well as the relative depths must be measured. (That is done by the system itself, and the figures are put into the system controller automatically).

The accuracy of the LBL system is mainly dictated by the geometry of the transponder array and the location of the vessel in the array, the actual S/N, and the errors in sound velocity. The accuracy is however to a little extent influenced by the range (depth).

In the following, the accuracy of a LBL system is shown by three cases. (It should be noticed that LBL performance calculations may be simulated on the HPR or HiPAP system controller).

The following "one sigma" error contribution to the range measurements are assumed:

- Range reception with 20 dB S/N: 0.15 meter
- Range reception with 12 dB S/N: 1.02 meter
- Range reception in the transponder: 0.15 meter
- Range error due to transponder.movement: 0.10 meter
- Range error due to rig movement: 0.20 meter

The random errors are added as Gaussian noise to the measurements.

The figure shows the error in the horizontal position when the Drilling Unit moves within the transponder array. The simulations are done with 4 LBL transponders placed on the seabed in a circle with radius 636 m. The water depth is 1200 m.

→ *Refer to figure on page 40.*

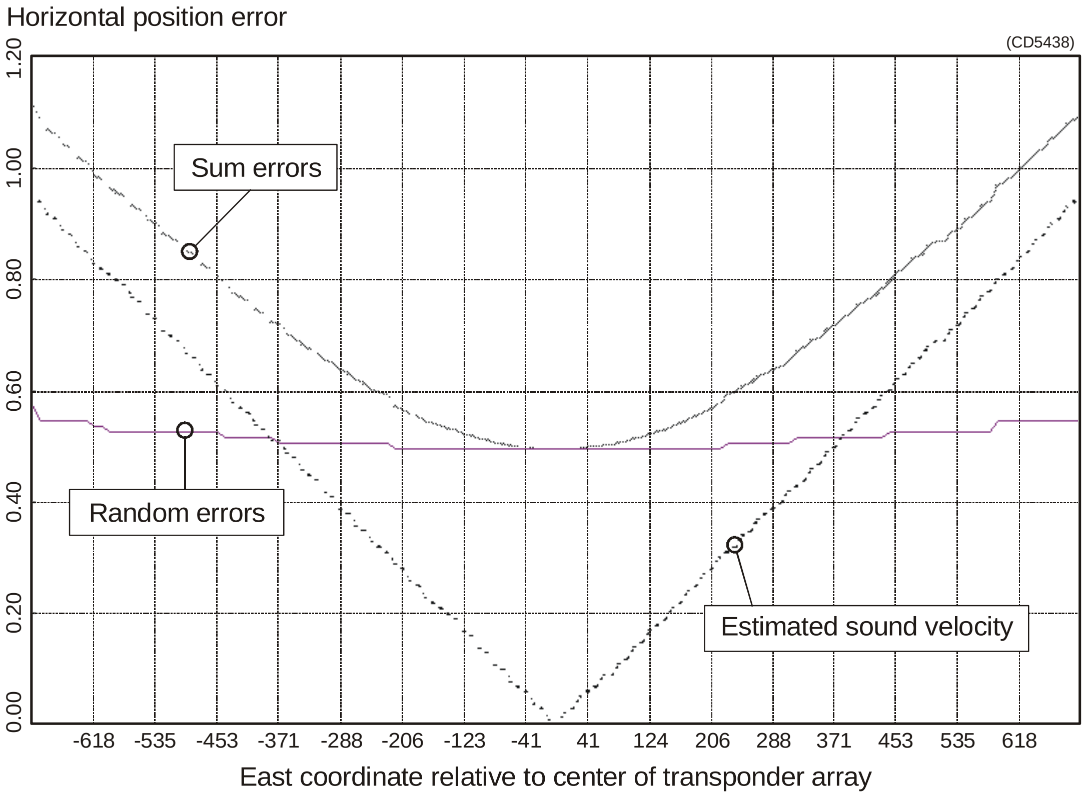

Figure 28 - Horizontal position error when positioning a Drilling Rig in the LBL standard mode.

The water depth is 1200 m. The four seabed transponders are on a circle with radius 636 m. A Signal-to-noise ratio of 20 dB is assumed at the receiving end.

The error is showed as a function of the East coordinate. The North coordinate is zero, and the East coordinate zero is consequently the centre of the array. We have assumed that the wide beam of the positioning transducer is used, and that the S/N when receiving the replies from the transponders is 20 dB.

The random errors are approximately the same as long as the rig is within the area covered by the array.

The effect of a systematic error in the Sound velocity of 1 m/s is also showed. When being in the centre of the array, that error causes no position error. When being in the outer parts of the array, that error causes a significant systematic error in the position.

The random position error is showed for three different cases in table 1. Case 1 is the same as shown in figure 28. In the next two cases the water depth is increased to 2000 m. In case 2 the transponder array is smaller, allowing narrow beam transducers to be used both on the Drilling Unit and in the transponders. Then we assume 20 dB S/N when receiving the transponder replies. In case 3 the transponder array is bigger, and wide beam transducers have to be used. The S/N is therefore assumed to be 12 dB.

The relative geometry (i.e. the angles) in case 1 and 3 are the same. The difference is the S/N. We see that the accuracy in case 3 is reduced due to a worse S/N.

The S/N in case 1 and 2 is the same. The geometry in case 1 is better than in case 2, giving a better position accuracy.

Case	**Water depth**	**Transponder array**	**S/N**	**Random error in horizontal position**
1	1200 m	4 Seabed transponders on a circle with radius 636 m (Wide beam array).	20 dB	0.50 m
2	2000 m	As above, but radius 500 m. (Narrow beam array)	20 dB	0.95 m
3	2000 m	As above, but radius 1060 m. (Wide beam array)	12 dB	1.17 m

Table 1 Random errors in the horizontal position for three LBL cases

8.4 Multi-user long base line (MULBL) systems

Introduction

Existing Long base line (LBL) systems are limited to one user at a time. The limitation in existing systems makes an operation where several vessels and/or ROVs need to be positioned simultaneously in LBL impossible. This is an actual problem situation both in field development and in survey. In order to have an unlimited number of vessels operating in the same transponder Array, Kongsberg Simrad has introduced a Multiuser LBL (MULBL) system for positioning surface vessels and ROVs.

Description

We assume that one of the transponders in the array has communication with all the others in the array. It may be in the centre of the array. It is used as the Master in the positioning phase. The other transponders are called the Slaves.

The Master transponder acts as a beacon. It starts a positioning sequence by doing the steps described below. It is done regularly with an interval set on telemetry from one of the vessels.

1. The Master interrogates the Slaves in the array by transmitting the common LBL interrogation channel to them.
2. After a "turnaround" delay from its own interrogation, the Master transmits its individual transponder channel to be received by the vessels/ROVs positioning in the array.
3. Each Slave transponder receives the interrogation from the Master beacon and transmits its individual reply channels after a turnaround delay.

The Slaves in the transponder array are commanded to listen for the LBL interrogation channel transmitted by the Master Beacon. It is in the telemetry band, just as when a Master transponder interrogates a Slave transponder in the local calibration phase. The transponders have turnaround delays just as in the standard positioning mode.

An HPR positioning in the array listens for the individual channels transmitted by the master beacon and by the Slave transponders. When they are received, HPR uses its knowledge about their positions in the transponder array to calculate the differences in range to the beacon/transponders in the transponder array. The time difference **t** between the Master interrogation and the start of the reception of the pulses at the HPR is unknown. It has to be calculated together with the position of the vessel or ROV. This requires an extension in the existing LBL algorithm.

The principle is illustrated below. It is similar to Loran C surface navigation systems.

→ *Refer to figure on page 43.*

Quality factors

MTBF figures for the different systems are based on records of experience.

The MTBF of a HiPAP system with Transducer, hull unit, transceiver unit, controller, display and cabling is 24 000 hours.

The MTBF of a HPR 400 SSBL and LBL system with narrow beam transducer, hull unit, transceiver unit, controller, display and cabling is 20 000 hours.

Transponders type SPT and MPT has a MTBF like 40 000 hours.

Integrity in this context means the system ability to check its measurements continuously. That is possible when it has more measurements available than necessary, i.e. the calculations are overdetermined.

A LBL systems perform a high degree of integrity by:

- Using two receiving transducers/transceiver inputs and perform a double set of calculations.
- Using SSBL measurements simultaneously.
- Using more than three transponders.

SSBL/HiPAP systems perform a high degree of integrity if:

- Measures on two or more transponders, compare position and observes the relative positions regularity.
- If there are two or more transducers at the ship that monitores and compares the transponder replies (Dual HiPAP).

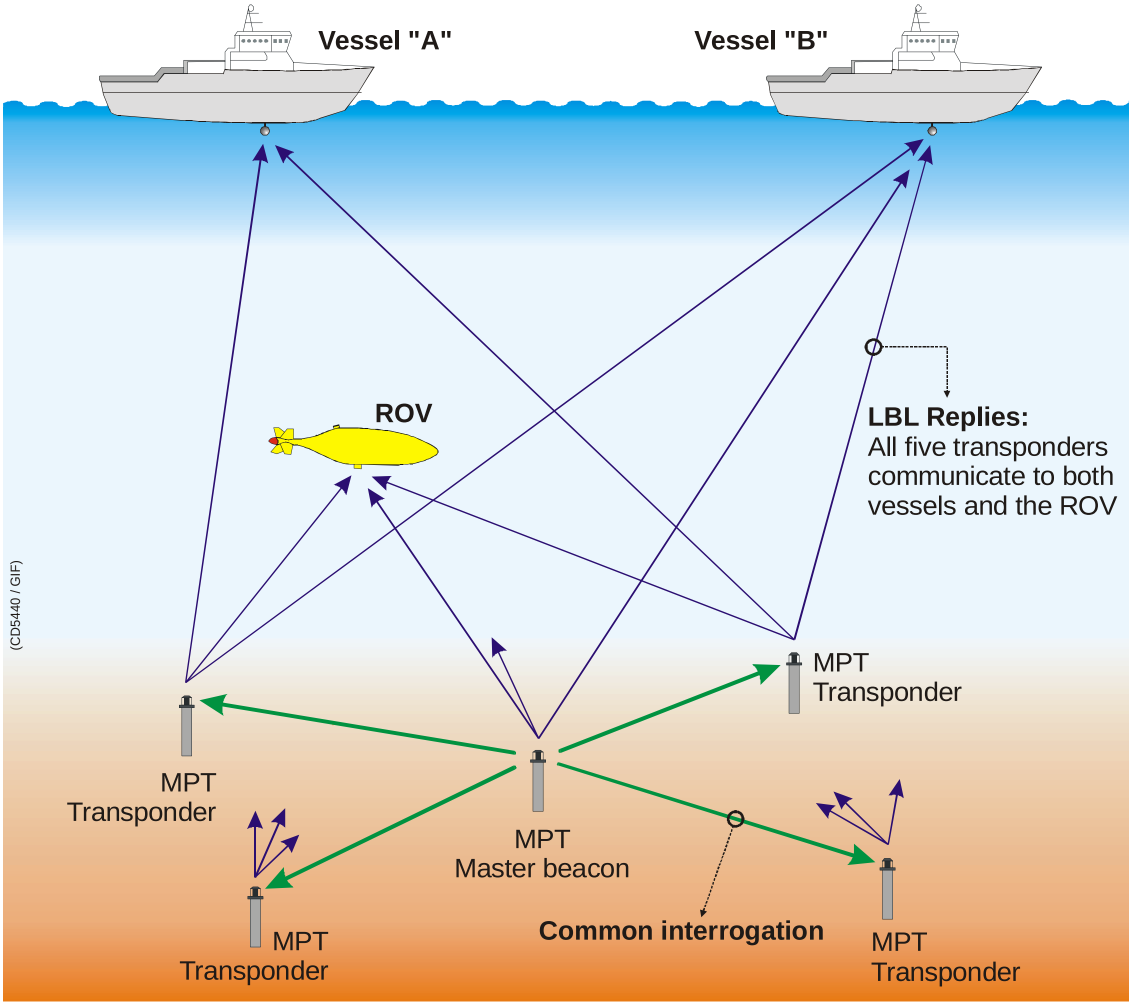

Figure 29 - Scenario with two vessels and one ROV / UUV positioning in a "Synchronised Beacon Array".

Availability figures means the time the dynamic positioning system can use the data from the reference system.

In this context, the HPR is *available* if or when the signal-to-noise (S/N) ratio allows for an error less than required from the dynamic positioning system. Further, any missing replies will reduce the availability. Missing replies are caused by poor S/N.

The following table states the availability figure versus S/N:

Signal to Noise Ratio:	**12 dB**	**15 dB**	**20 dB**	**25 dB**
Availability:	85%	99%	100%	100%

Table 2 Availability versus Signa-to-noise (S/N)

These are theoretical figures based on the actual signal processing in the system.

If the HPR system are mounted on a shallow hull, the HPR transducer may be blocked by air in heavy weather conditions. Also jet or flow from propellers may block the HPR systems. Experience shows that necessary contingency are obtained by installing two or more transducers on opposite sides of the ship or rig. It is obvious that heavy conditions may influence the availability of the HPR system.

However, we have no record available to make a complete list of availability figures versus weather conditions at various depths for different ships and rigs.

9 SUMMING UP

Typical parameters reducing/limiting acoustic performance:

- Nature related
  - ray bending
  - reflections (seabed and surface)
  - sea noise
  - transmission loss
- Equipment related
  - vessel noise
  - transmit power
  - receiver sensitivity
  - acoustic interference (other systems)

Deep water considerations:

- Use systems with high directivity (narrow transducer beam), both for top-side and transponders.
- Use high power transponders (or responders)
- Use high accuracy motion sensors

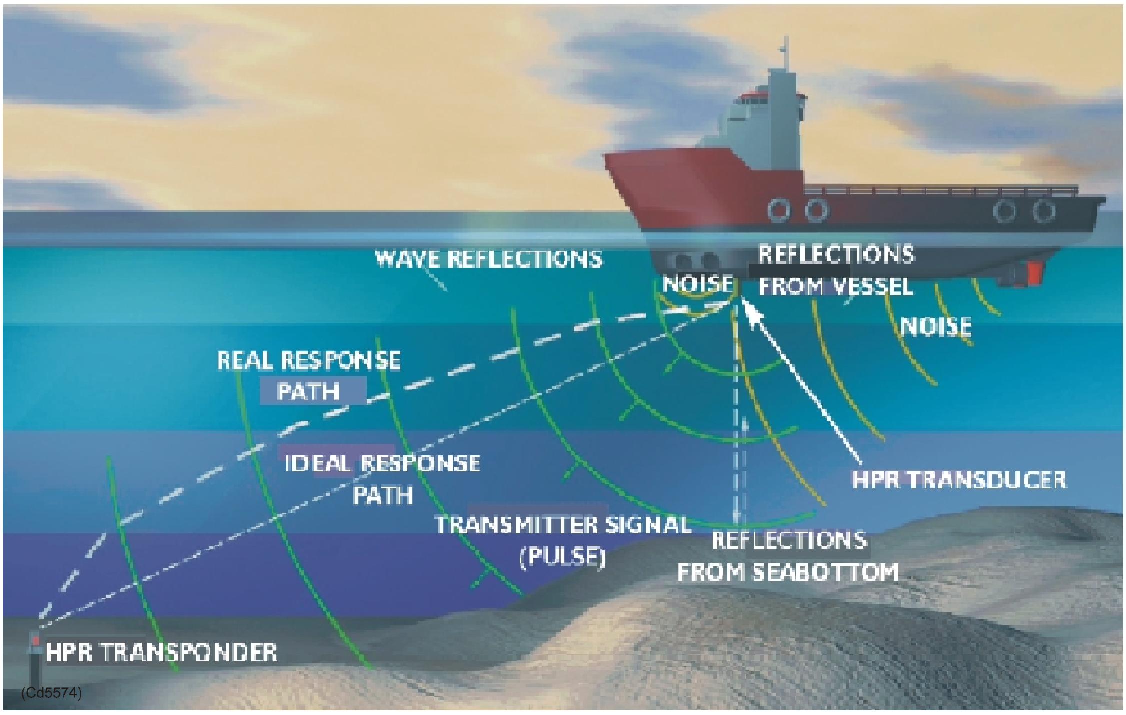

Figure 30 - Underwater acoustic

10 BASIC ACOUSTIC FORMULAS

Wave length

$$\lambda = \frac{c}{f}$$

where:

λ = wavelength (in meters)

c = speed of sound in water (in meters/second)

f = frequency (in Hz)

Pulse length

$$Pulselength = \frac{c \cdot \tau}{2}$$

where:

c = speed of sound in water (in meters/second)

τ = pulse duration (in seconds)

Intensity

$$I = \frac{p^2}{\rho \cdot c}$$

where:

I = intensity

p = pressure

c = speed of sound in water (in meters/second)

ρ = water density

Decibel

$$10 \log \frac{I}{I_o} = 10 \log \frac{p^2/\rho c}{p_0^2/\rho c} = 20 \log \frac{p}{p_o}$$

where:

I = intensity

I_o = referenced intensity

p = pressure

p_o = referenced pressure, normally 1 μPa

ρ = water density

Geometrical spreading

$$\frac{I_o}{I} = (\frac{r}{r_o})^2$$

$$TL_1 = 10\log\frac{I_o}{I} = 20\log\frac{r}{r_o}$$

where:

r = range (in meters)

r_o = referenced range, normally 1 meter

I = intensity

I_o = referenced intensity

Absorption loss

$$TL_2 = \alpha(r - r_o) \ when \ r_o \ll r$$

$$TL = \alpha r$$

where:

r = range (in meters)

r_o = referenced range, normally 1 meter

α = absorption coefficient (in dB/m)

One-way transmission loss

$$TL = 20\log r + \alpha r$$

where:

r = range (in meters)

α = absorption coefficient (in dB/m)

Two-way transmission loss

$$2TL = 40\log r + 2\alpha r$$

where:

r = range (in meters)

α = absorption coefficient (in dB/m)

Transducer beam pattern

$$\beta = \frac{\lambda}{L} \cdot \frac{180}{\pi}$$

where:

β = beam width (in degrees)

λ = wavelength

L = Length of active transducer area (in meter)

The near field

$$r = \frac{L^2}{\lambda}$$

where:

r = range (in meters)

λ = wavelength

L = Transducer's longest side (in meter)

Directivity factor

$$D = \frac{I_o}{I_m}$$

where:

I_o = radiated intensity at the transducer axis

I_m = mean intensity for all directions

Directivity index

$$DI = 10 \log D$$

$$D = \frac{2.47}{\sin\frac{\beta_1}{2} \cdot \sin\frac{\beta_2}{2}}$$

where:

$\beta_1 = \beta_2$ = transducer opening angle (in degrees)

Equivalent ideal beam pattern

$$\psi = \frac{\beta_1 \cdot \beta_2}{5800}$$

where:

$\beta_1 = \beta_2$ = transducer opening angle (in degrees)

Source level (SL)

$$SL = S_i + 20 \log i$$

where:

S_i = transmitting response (in dB re 1 μPa per Ampere)

i = transducer current (in Ampere)

$$SL = 170.9 + 10 \log P + E + DI$$

where:

P = transmitter power (in watt)

E = $10 \log \eta$

η = transducer efficiency (approximately 0.5 for ceramic transducers)

DI = directivity index

Target strength (TS)

$$TS = 10\log\frac{I_r}{I_i}$$

where:

I_i = incident sound intensity

I_r = reflected sound intensity 1 meter from sound centre

Target strength (TS) of a large sphere

$$TS = 10\log\frac{\alpha^2}{4}$$

where:

α = radius of sphere (in meters)

Sonar equation

$$EL = SL - 2TL + TS$$

where:

EL = echo level at transducer

Position standard deviation

$$\delta_{k,y} = \frac{\phi}{2}\sqrt{\frac{1 + S/N_{bm}}{S/N_{bm}^2}}$$

$$\delta_{tot} = \delta_{x,y}\sqrt{\frac{\pi}{2}}$$

where:

δ = standard deviation

ϕ = transducer optimum angle (in degrees)

S/N_{bm} = signal-to-noise power ratio in a beam

Notes

Notes

11 MAIN INDEX

The next pages presents the main index of this manual.