Introduction to sonar

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This paper gives a short introduction to underwater sound and the principle of sonar. In addition, the paper describes the use of sonar in three different applications: fish finding; mapping of the seafloor and imaging of the seafloor.

I. INTRODUCTION

SONAR is the acronym for **SO**und **N**avigation **A**nd **R**anging. Sonar techology is similar to other technologies such as: RADAR = **RA**dio **D**etection **A**nd **R**anging; ultrasound, which typically is used with higher frequencies in medical applications; seismics, which typically uses lower frequencies in the sediments.

The knowledge and understanding of underwater sound is not new. Leonardo Da Vinci discovered in 1490 that acoustics propagate well in the ocean:

> *"If you cause your ship to stop and place the head of a long tube in the water and place the outer extremity to your ear, you will hear ships at a great distance from you"*

The first active sonar designed in the same way modern sonar is, was invented and developed as a direct consequence of the loss of *Titanic* in 1912, where the basic requirement was to detect icebergs in 2 miles distance.

Underwater sound is used both by whales and dolphins (see Fig. 1) for communication and echolocation.

FIG. 1 Experts in underwater sound. From wikipedia.org. Courtesy of NASA and Zorankovacevic.

A. Basic physics

Sound is pressure perturbations that travels as a wave. Sound is also referred to as compressional waves, longitudal waves, and mechanical waves (see Fig. 2). The acoustic vibrations can be characterized by the following:

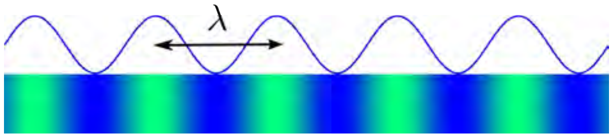

FIG. 2 A sound wave is a longitudal perturbation of pressure

- Wave period T [s]
- Frequency $f = 1/T$ [Hz]
- Sound speed c [m/s]
- Wavelength $\lambda = c/f$ [m]

A small note about units. Logarithmic scale, and in particular the Decibel scale (referred to as dB), is often used in sonar literature (including this paper). The dB scale is defined as

$$I_{dB} = 10 \log_{10}(I) \tag{1}$$

where I_{dB} is intensity in dB and I is linear intensity. Hence 10 dB means a factor 10, 20 dB means a factor 100, 30 dB means a factor 1000 etc.

The reason for using the logarithmic scale is that the acoustic signal strength varies several orders of magnitude over a typical distance travelled.

B. More information

Much literature has been written about underwater sound and sonar, due to the popularity of the technology and the complexity of the medium. This small review is inspired mainly by Xavier Lurton's excellent book *An introduction to underwater acoustics: Principles and Applications* (Lurton, 2002, 2010). `www.wikipedia.org` has also a very detailed web page both on sonar and underwater sound. See also (Burdic, 1984; Fish and Carr, 2001; Nielsen, 1991; Urick, 1983) for more details on sonar. Underwater acoustics is a field in it self as part of theoretical acoustics (Brekhovskikh and Lysanov, 1982; Medwin and Clay, 1998; Tolstoy and Clay, 1987). Sonar imaging and array signal processing is well covered in (Johnson and Dudgeon, 1993).

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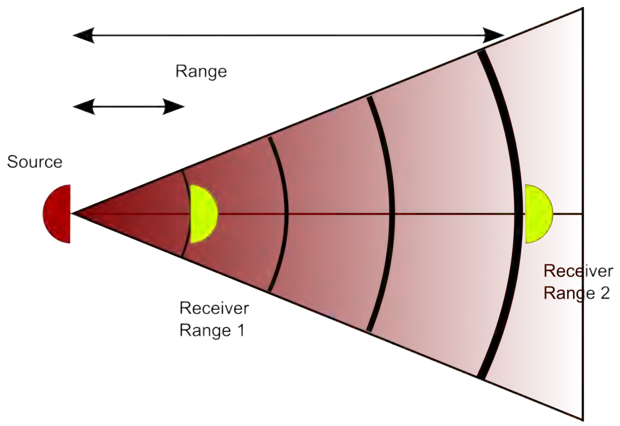

FIG. 3 One way spherical spread.

II. UNDERWATER SOUND

In this section we describe the main factors that affect underwater acoustic propagation in the ocean: Loss and attenuation, refraction, scattering and noise.

A. Spherical spread

The acoustic wave expands as a spherical wave in a homogeneous medium, as shown in Fig. 3. The acoustic intensity I decreases with range R in inverse proportion to the surface of the sphere as

$$I \sim \frac{1}{R^2} \tag{2}$$

in homogeneous media.

For two way propagation, the acoustic wave expands as a spherical wave to the reflector. Then, the reflector sphreads the signal in all directions, and the reflected field expands as a spherical wave back to the receiver. In a homogeneous medium, the two way loss becomes

$$I \sim \frac{1}{R^2}\frac{1}{R^2} = \frac{1}{R^4} \tag{3}$$

B. Absorption

Seawater is a dissipative medium through viscosity and chemical processes. Acoustic absorption in seawater is frequency dependent, such that lower frequencies will reach longer than higher frequencies.

The frequency relation to absorption is such that the travelling distance measured in wavelengths has a fixed absorption loss. This is summarized in Table I. Fig. 4 shows the absorption coefficient in dB per km for frequencies from 100 Hz to 1 MHz for 4 different temperatures. The absorption coefficient is a function of temperature, salinity, depth (pressure) and pH in addition to frequency.

f [kHz]	R [km]	λ [m]
0.1	1000	15
1	100	1.5
10	10	0.15
100	1	0.015
1000	0.1	0.0015

TABLE I Maximum range R for frequency f and corresponding wavelength λ.

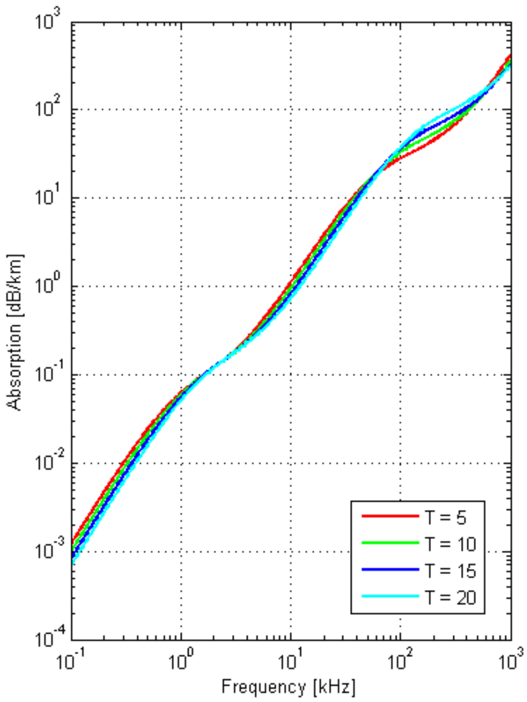

FIG. 4 Absorption coefficient.

C. Refraction

Consider a plane interface between two different media with different sound velocity c_1 and c_2. A plane incoming acoustic wave will partly reflect where the reflection angle is equal to the incident angle, and partly refract into the other medium. This is illustrated in Fig. 5. The angle of refraction is given by Snell's law

$$\frac{\sin\theta_1}{c_1} = \frac{\sin\theta_2}{c_2}. \tag{4}$$

The sound velocity in the ocean can be approximated with the following empirical formula:

$$\begin{aligned} c = 1449.2 + 4.6T - 0.055T^2 + 0.00029T^3 \\ + (1.34 - 0.010T)(S - 35) + 0.016D \end{aligned} \tag{5}$$

where T is temperature in degrees Celsius, S is salinity in parts per thousand, and D is depth in meters. Hence, sound velocity contains information about the

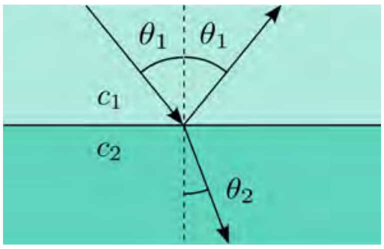

FIG. 5 Snell's law.

ocean environment. As an example: $T = 12.5$ °C, $S = 35$ ppt, $D = 100$ m gives $c = 1500$ m/s.

The deep water sound velocity, shown in Fig. 6, can be divided into four different regions:

- The surface layer
- The seasonal thermocline
- The permanent thermocline
- The deep isothermal layer

Since the sound velocity continuously changes with depth, an *acoustic ray* will continuously refract into a new direction. The rate at which the ray changes direction is directly proportional to the gradient of the sound velocity (see equation (4)). Fig. 7 shows three example rays with different initial angles, in an upwards refracting sound velocity profile. For constant gradient in the sound velocity, the rays become parts of circles. Note that the aspect ratio in the figure is not correct.

For a sound velocity profile with a local minimum, the acoustic signals may be trapped by the effect of refraction. This causes an underwater sound channel, where in effect, the mean acoustic intensity in the sound channel no longer spreads spherically, but cylindrically. This gives a spreading loss of $I \sim 1/R$ as opposed to $I \sim 1/R^2$ for spherical spread, which again gives much longer propagation range within the channel. Fig. 8 shows three rays from a source at 300 m water depth. The rays are trapped in the sound channel formed by the permanent thermocline and the deep isothermal layer. It is known that whales communicate over thousands of kilometers by using underwater sound channels.

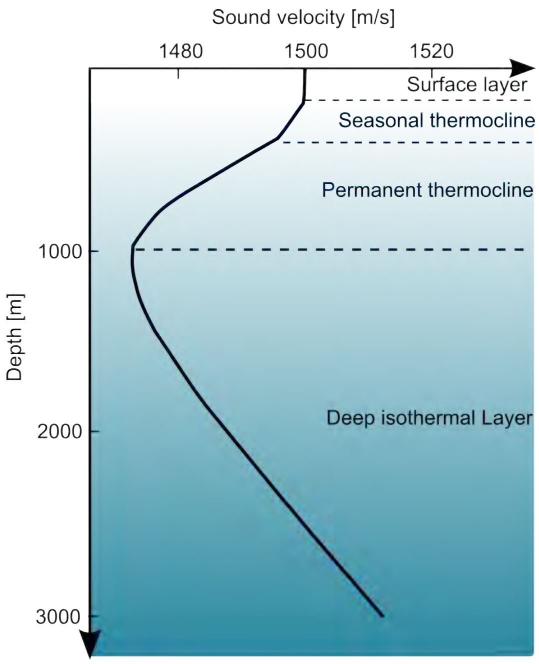

FIG. 6 Deep water sound velocity.

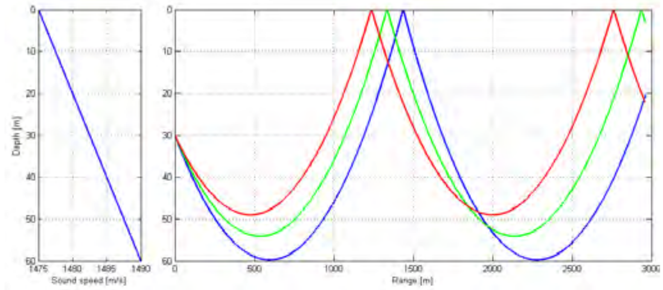

FIG. 7 Raytrace of sound in an upwards refracting environment.

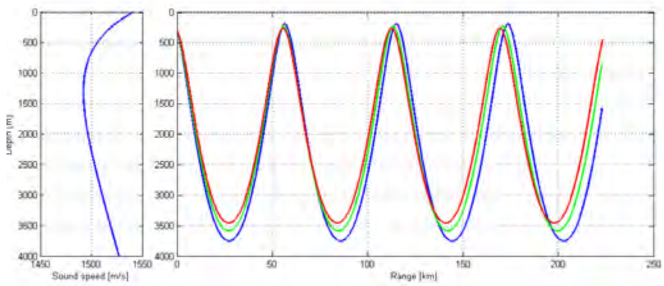

FIG. 8 Raytrace of underwater sound channel.

D. Reflection

Consider the interface between two different media, as shown in Fig. 5. A plane incident acoustic wave will partly reflect and refract at the interface (given by Snell's law). The amplitude of the reflected and refracted wave are determined by the angle of incidence and the material properties given by the characteristic impedance

$$Z_0 = \rho c \tag{6}$$

where ρ is the density [kg/m^3] and c is the sound speed [m/s]. At normal incidence, the reflection coefficient is

$$V = \frac{Z - Z_0}{Z + Z_0} \tag{7}$$

and the transmission coefficient is

$$W = \frac{2Z_0}{Z + Z_0} = 1 - V. \tag{8}$$

Material	Impedance
Air	415
Seawater	1.54×10^6
Clay	5.3×10^6
Sand	5.5×10^6
Sandstone	7.7×10^6
Granite	16×10^6
Steel	47×10^6

TABLE II Characteristic impedance is a material property.

Thus, by operating the sonar in a known environment (with known Z_0), estimating the reflection coefficient from a plane interface to an unknown medium, the characteristic impedance Z can be calculated, and thereby the material properties determined. Table II lists the characteristic impedance to a few different media. Note that this description is not valid when the second medium is absorbing or is elastic.

As an example, consider reflection from the sea surface seen from beneath (as illustrated in the left panel of Fig. 9). Using the characteristic impedance for air $Z = 415$ and seawater $Z_0 = 1.54 \times 10^6$, we get a reflection coefficient of

$$V = \frac{Z - Z_0}{Z + Z_0} \approx -1 \tag{9}$$

which states that the sea surface is a perfect acoustic reflector.

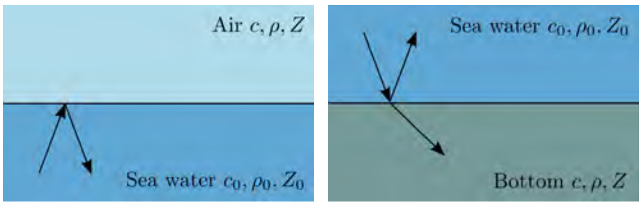

FIG. 9 Reflection in the sea-air interface (left) and the sea-bottom interface (right).

Now, we consider reflection from the seafloor. A sandy seafloor with characteristic impedance of $Z = 5.5 \times 10^6$, the reflection coefficient becomes

$$V = \frac{Z - Z_0}{Z + Z_0} \approx 0.56 \tag{10}$$

for normal incidence. Similarly, a hard rock on the seafloor will have a characteristic impedance of $Z = 16 \times 10^6$ (for granite), which gives a reflection coefficient of

$$V = \frac{Z - Z_0}{Z + Z_0} \approx 0.82. \tag{11}$$

E. Scattering

Scattering of acoustic waves can be of two categories in the ocean:

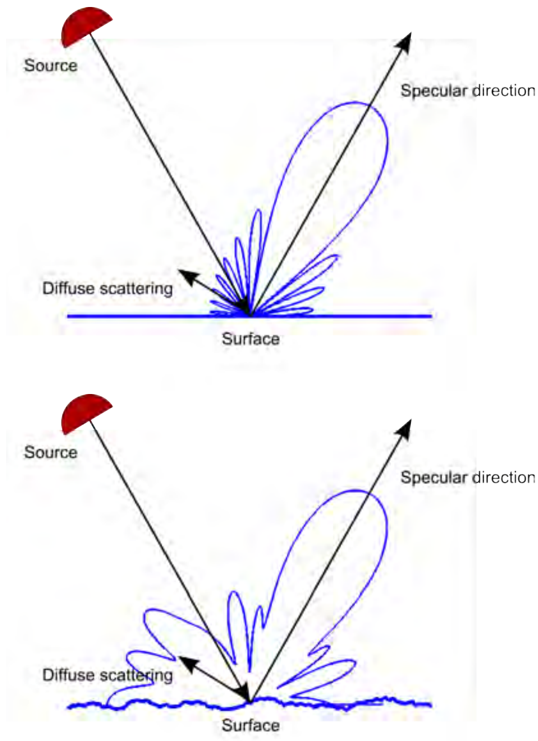

FIG. 10 Upper: Sound scattering from a smooth surface. Lower: Sound scattering from a rough surface.

1. Surface scattering from the sea surface or from the seafloor.
2. Volume scattering from ocean fluctuations, marine life or objects.

Surface scattering from a smooth surface compared to the acoustic wavelength (shown in the upper panel of Fig. 10) will mainly give specular reflection.

If the surface is rough, some part of the reradiated acoustic energy will be scattered diffusely in random directions, as shown in the lower panel of Fig. 10. The more rough the surface is, the more acoustic energy will be scattered diffusely.

For non-normal incident waves, such that specular reflection cannot reach the observer, the surface has to be rough in order to facilitate any observed scattered signals. The scattered field is dependent on the roughness of the surface (relative to the wavelength) and the characteristic impedance (or difference between media).

F. Ocean fluctuations

In coastal areas and in the upper layer, random variability will affect acoustic propagation. These effects (see Fig. 11) are ocean turbulence, currents, internal waves (gravity waves in density variations below the sea surface), the sea surface and microbubbles. Ocean acoustics can be used to monitor and estimate these variations.

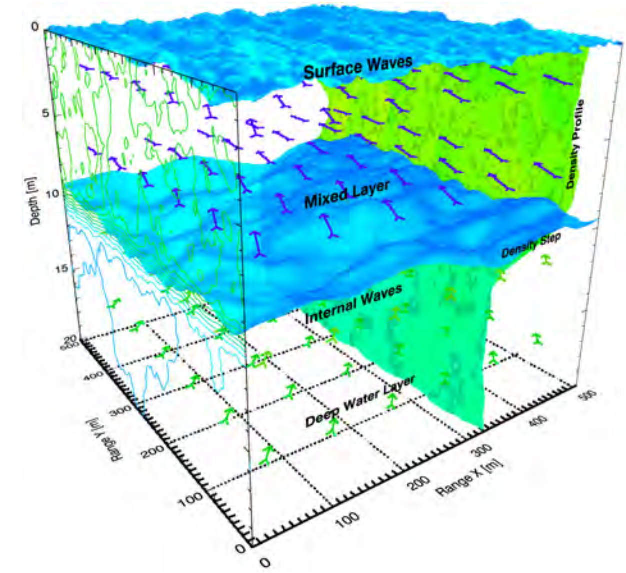

FIG. 11 Random variability in the ocean.

This is called acoustical oceanograhpy.

III. PRINCIPLES OF SONAR

There are two different operational modes for sonar:

1. *Passive sonar*, where an acoustic noise source is radiated by the target, and the sonar only receives the acoustic signals (see Fig. 12).

2. *Active sonar*, where the sonar itself transmits an acoustic signal, which again propagates to a reflector (or target), which again reflects the signal back to the sonar receiver (see Fig. 13).

In the following section, we will describe the basic principle of echo location for active sonar. We also list the components involved in the signal processing for active sonar.

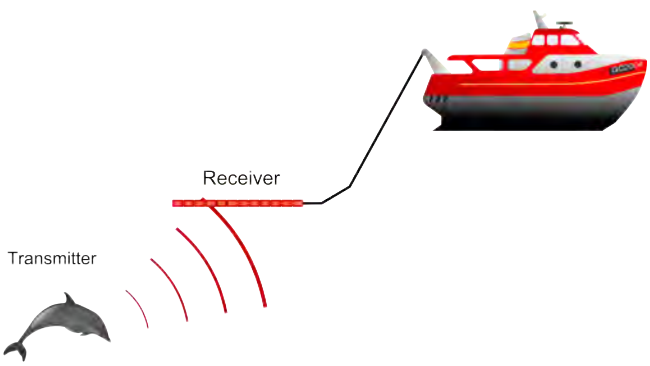

FIG. 12 Passive sonar.

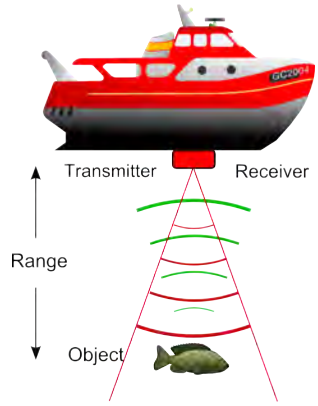

FIG. 13 Active sonar.

A. Range estimation

Range defined as the radial distance between the sonar and the reflector, can be estimated as follows (see Fig. 14):

- A short pulse of duration T_p is transmitted in the direction of the reflector.
- The receiver records the signal until the echo from the reflector has arrived
- The time delay τ is estimated from this time series

The range to the target is then given as

$$R = \frac{c\tau}{2} \qquad (12)$$

The sound velocity c has to be known to be able to map delay into space.

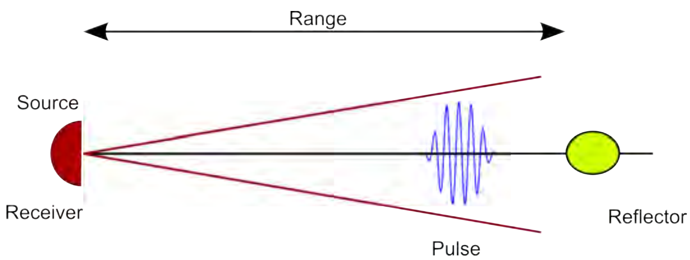

FIG. 14 Estimation of range.

The accuracy of which the range is estimated is related to the pulse length T_p for traditional pings (or gated CW pulses)

$$\delta R = \frac{cT_p}{2}. \qquad (13)$$

This is equivalent to the *range resolution* defined as the minimum spacing two echoes can be seperated and still detected (see Fig. 15). A shorter pulse gives better range resolution. However, shorter pulses has less energy in the pulse, which again gives shorter propagation range. An alternative to this is to modulate (or phase code) the

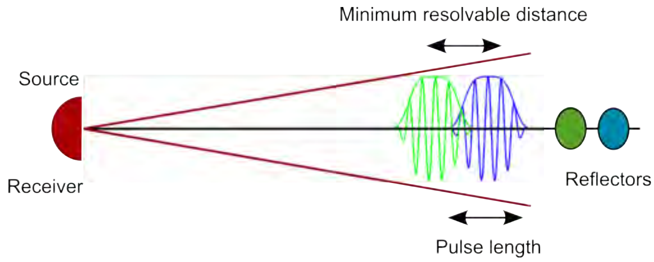

FIG. 15 Range resolution.

pulse. For phase coded pulses, the resolution is

$$\delta R = \frac{c}{2B} \tag{14}$$

where B is the bandwidth (or frequency spread) of the acoustic signal. (14) actually covers (13), since

$$B = \frac{1}{T_p} \tag{15}$$

for gated CW signals.

B. Bearing estimation

There are two key elements involved in the estimation of direction (or bearing) in sonar

1. The electro-acoustic transducer and its size
2. The grouping of transducers into arrays

A transducer (or antenna or loudspeaker) is directive if the size of the antenna is large compared to the wavelength. The directivity pattern generally contains a main lobe, with a *beamwidth* (or field of view)

$$\beta \approx \frac{\lambda}{D} \tag{16}$$

where D is the diameter (or length) of the antenna. This is shown in Fig. 16.

We note that the beamwidth is frequency dependent. Higher frequency gives narrower beam for a given antenna size. Or, conversely, higher frequency gives smaller antenna size for a given angular spread. This is the single most important reason to choose high frequencies in sonar imaging.

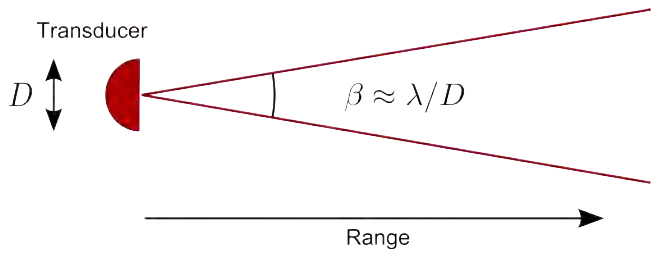

FIG. 16 Transducer directivity.

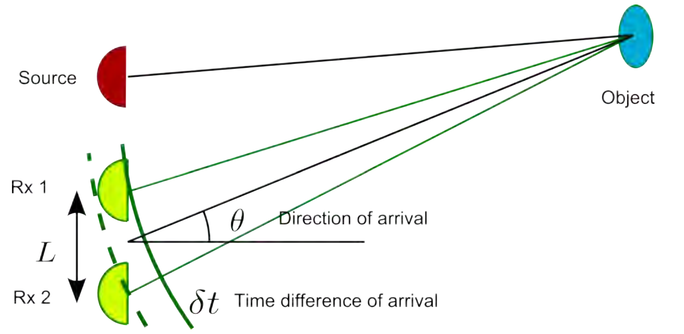

FIG. 17 Direction of arrival.

The direction of arrival (or bearing) from a reflected signal or an external source, can be estimated from the time difference of arrival δt between two different receivers spaced L apart (see Fig. 17)

$$\theta = \sin^{-1}\left\{\frac{c\delta t}{L}\right\}. \tag{17}$$

This can be calculated a number of ways:

1. Estimating the range to the reflector (as described above) for each receiver antenna
2. Direct comparison of the signals received by two antenna elements (by cross correlation)
3. Delaying each element in the array of receivers to steer the response of the array in different direction and then estimating at which direction maximum return is. This is known as *beamforming*.

For multiple antennas in the receiver array, multiple beams (or directions) can be calculated simultaneously (see Fig. 18).

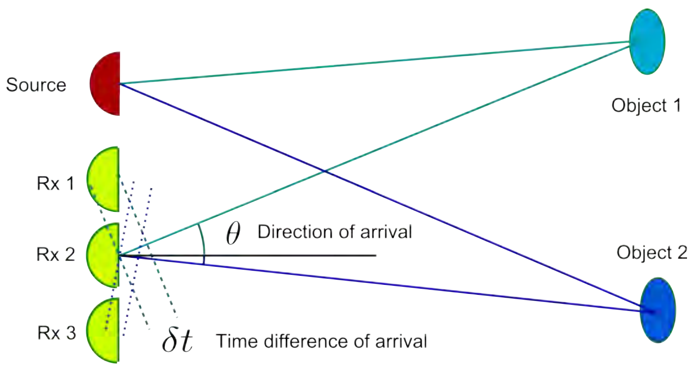

FIG. 18 Direction of arrival from multiple reflectors.

C. Imaging sonar

The principle of imaging sonar is to estimate the reflectivity for all calculated ranges and in all selected directions. This is illustrated in Fig. 19. The field of view is given by the angular width of each element. The angular (or azimuth) resolution is given by the array length measured in wavelengths. The range resolution is given by the bandwidth of the system.

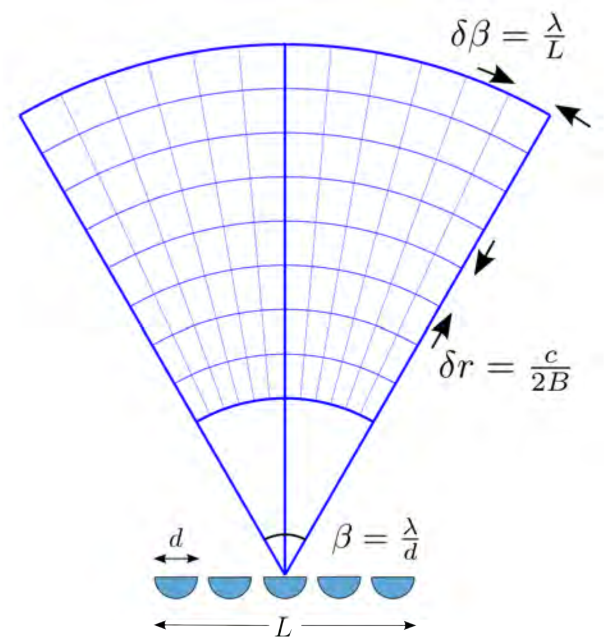

FIG. 19 Imaging sonar field of view and resolution.

D. Signal model

The basic signal model for an active sonar contains three main components (see Fig. 20):

1. The *signal* which has propagated from the transmitter, through the medium to the reflector, is backscattered, and then propagated back to the receiver. The backscattered signal contains the information about the target (or reflector) of interest. It depends on the physical structure of the target and its dimensions, as well as the angle of arrival and acoustic frequency.
2. *Reverberation* is unwanted echoes and paths of the transmitted signal. This is typically caused by surface and bottom scattering, and/or volume scattering.
3. *Additive noise* is acoustic signals from other sources than the sonar itself.

The sonar equation is an equation for energy conservation for evaluation of the sonar system performace. In its simplest form, the equation states the following:

$$Signal - Noise + Gain > Threshold \tag{18}$$

where $Threshold$ is the value for which the signal after improvement (gain) is above the noise level. A more

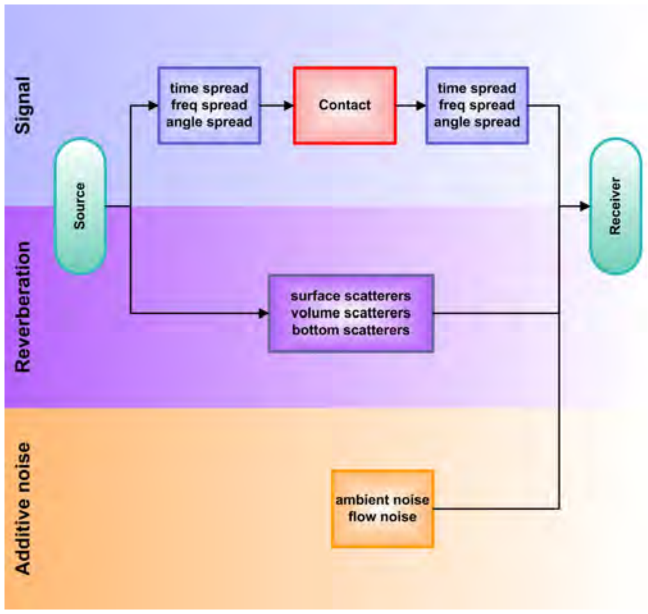

FIG. 20 Signal model.

detailed version for active sonar is:

$$SL - 2TL + TS - NL + DI + PG > RT \tag{19}$$

where SL is source level, TL is transmission loss, TS is target strenght, NL is noise level, DI is directivity index, PG is processing gain, and RT is reception threshold. Note that the sonar equation describes logarithmic intensity in dB. Fig. 21 shows the received time series (or range profile) for a single ping of data with a target of interest.

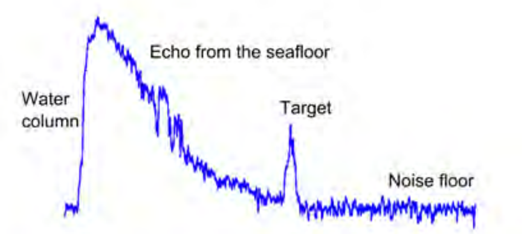

FIG. 21 Example range profile.

E. Signal processing

Active sonar signal processing can be divided into a number of different stages. With reference to Fig. 22, these are

- Preprocessing: filtering and applying time variable gain (TVG).

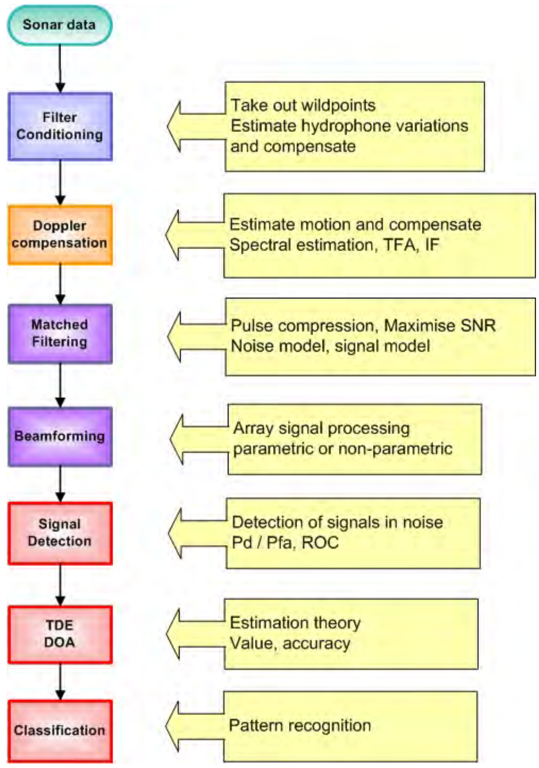

FIG. 22 Active sonar signal processing chain.

- Pulse compression: matched filtering in range (convert the time spread coded pulses to “delta”-functions).

- Beamforming: direction estimation (or matched filtering in azimuth). This is to convert element data in an array into directional beams (array signal processing).

- Detection: Detection of potential targets (i.e. a fish, a submarine).

- Parameter estimation: Estimation of position and velocity of the detected object.

- Classification: target recognition, pattern recognition.

IV. APPLICATIONS OF SONAR

In this section, we list three different applications of active sonar: fish finding, imaging of the seafloor and mapping of the seafloor. There are also other areas where sonar is widespread used, such as in military applications (i.e. finding submarines) and underwater navigation.

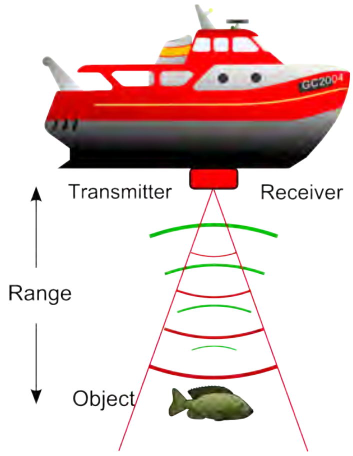

FIG. 23 Echosounding for fish finding.

A. Fish finding

Modern vessels for fisheries are usually well equipped with sonar systems. The basic usage of sonar is to detect and locate fish schools, as shown in Fig. 23. The most basic sonar type is the downward looking echosounder for range positioning of the fish. By moving the ship forward, a 2D scan (or slice) of the ocean is produced. Typical frequencies used are 20 kHz to 200 kHz, where the different frequencies have different depth rating (see Fig. 24).

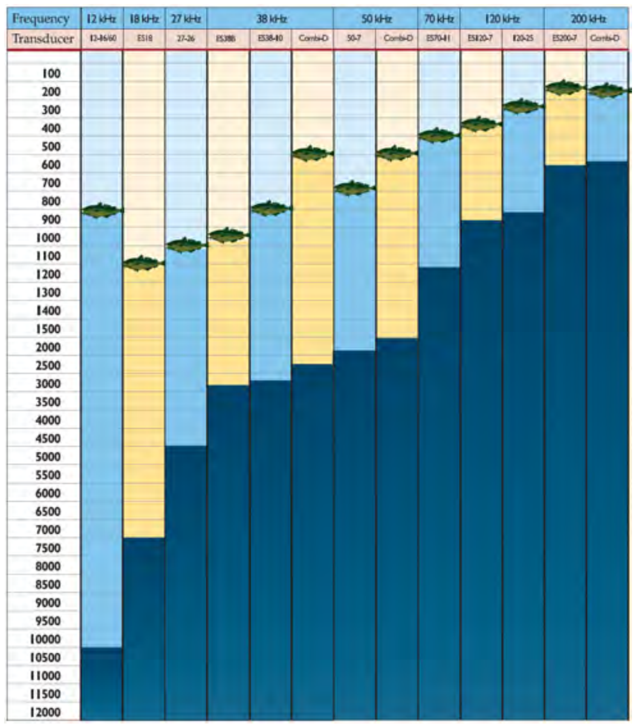

FIG. 24 Fish detection range (vertical axis) for different sonars operating at different frequencies. From www.simrad.com. Courtesy of Kongsberg Maritime.

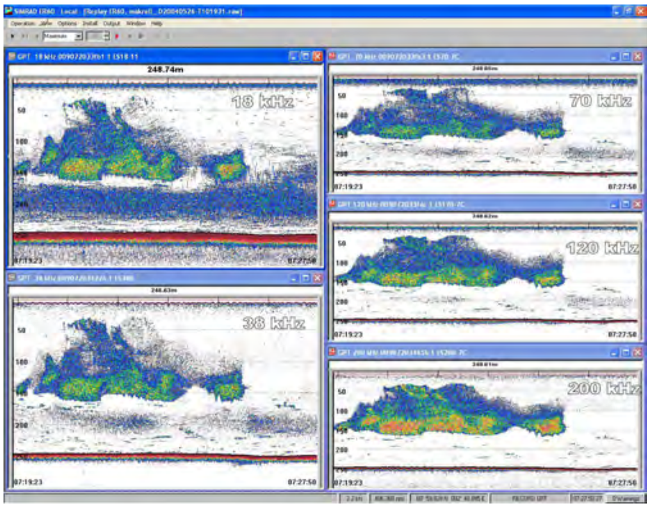

FIG. 25 Stock abundance and species characterisation with multifrequency echosounders. From www.simrad.com. Courtesy of Kongsberg Maritime.

Fish finders use the estimated target strength from the backscattered signal, to calculate fish size (or biomass). A fundamental challenge in this is to control every other term in the sonar equation, such that the target strength can be reliably estimated. If the vessel is equipped with echosounders at different frequencies, the difference in target response at the different frequencies can be used for species characterisation. Fig. 25 shows the echogram of a fish school at different frequencies.

B. Seafloor mapping with multibeam echosounders

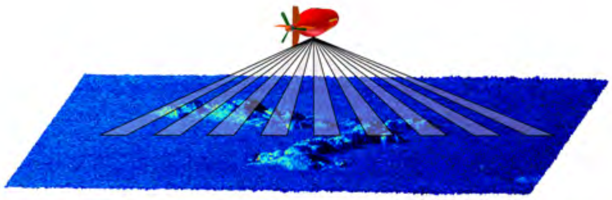

FIG. 26 Multibeam echosounder geometry.

The principle of mapping the seafloor with multibeam echosounders is as follows (see Fig. 26):

- The multibeam echosounder forms a large number of beams for each ping. The beams are in different direction, spanning a fan cross-track of the vehicle.
- Along each beam (or direction), the range (calculated from the time delay) to the seafloor is estimated.
- The range estimate in each beam gives the relative depth of the seafloor relative to the vehicle. This is again transformed into a map of the seafloor along the fan.
- The vehicle is moving forward, and consecutive pings gives a continuous map of the area surveyed.
- The map resolution is determined by the 2D beamwidth and the range resolution.

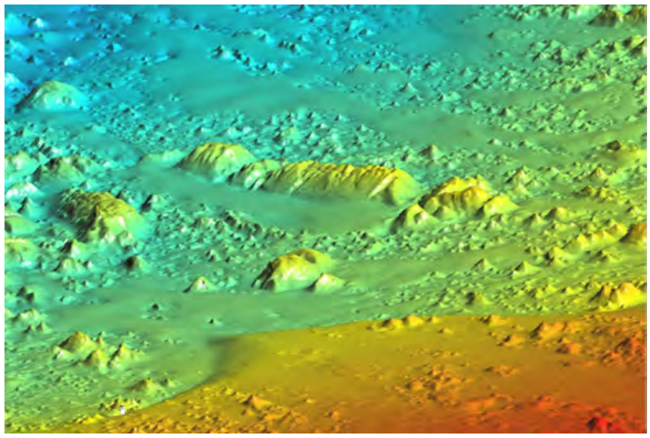

FIG. 27 Map of the Ormen Lange field produced by multibeam echosounder. Courtesy of Geoconsult / Norsk Hydro.

Multibeam echosounders are commonly used in mapping of the seafloor. Typical frequencies used are from 12 kHz for large scale hull mounted systems with full ocean depth range, to 450 kHz for short range high resolution mapping. The swath width of a multibeam echosounder is typically 4 to 10 times the sonar altitude (dependent on which system).

Fig. 27 shows an example map produced from data collected with a multibeam echosounder on the HUGIN AUV. The ridge in the map is 900 m long and 50 m high.

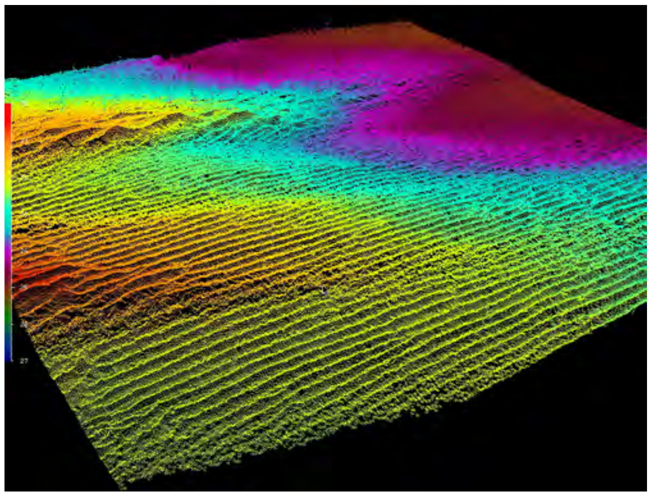

FIG. 28 Example map of sand ripples. Data collected by HUGIN AUV. Courtesy of Kongsberg Maritime / FFI.

C. Sonar imaging with sidescan sonar

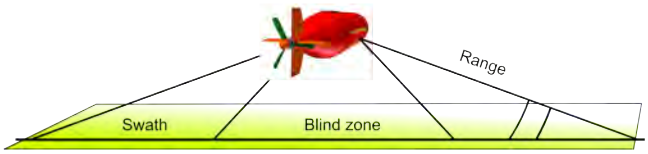

FIG. 29 Sidescan sonar geometry.

Sidescan sonar is used to produce acoustic images of the seafloor with high resolution. The sonar geometry is sidelooking (hence the name) as illustrated in Fig. 29. The principle is based on forming an acoustic image by moving the sonar forward and stacking the sonar response from succesive pings (see Fig. 30). The sidescan sonar works best when operated fairly close to the seafloor, typically mounted on a towfish (a towed lightweight vehicle), or an autonomous underwater vehicle (AUV) (as illustrated here). It can also be mounted on a surface ship hull when operated in shallow waters.

The operational frequencies for sidescan sonars are typically from 100 kHz to 1 MHz, with a opertational range from 500 m down to a few tens of metres. A common design in sidescan sonar is to choose the highest possible frequency for a given range (from calculations of absorpion) to obtain the best possible along-track resolution.

The area covered by a sidescan sonar is shown in Fig. 30. The cross-track coverage is given by the maximum range of the system, which again is related to pulse repitition interval and the maximum range of the acoustic signals (from absorption). The cross-track resolution is the range resolution, given by the pulse length (or the bandwidth for coded pulses). The along-track coverage is given by the pulse repitition interval. Finally, the along-track resolution is given by the directivity of the sonar antenna and the range.

D. Synthetic aperture sonar

A fundamental limitation to traditional sidescan sonar is the spatial resolution along-track (or azimuth). At far ranges, it is usually much worse than the range (or cross-track) resolution. The angular resolution is given by the array length measured in wavelengths. By decreasing the wavelength (or increasing the frequency), the angular resolution is improved. This, however, limits the practical range, due to the frequency dependent absorption is seawater. The other approach is to increase the length of the array. This, however, requires more hardware, more electronics and more space on the vehicle. Another approach is to synthesize a larger array by using consecutive pings from the moving sonar. This is the principle of synthetic aperture sonar (SAS) as illustrated in Fig. 31.

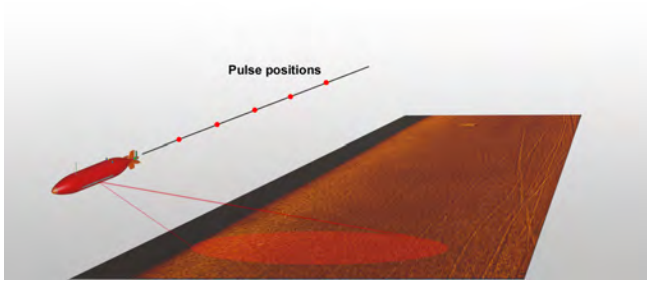

FIG. 31 Principle of synthetic aperture sonar.

By choosing the synthetic array (or aperture) to the maximum length given by the field of view for each physical element (see Fig. 32), the spatial along-track resolution becomes independent of both range and frequency. Existing SAS systems achieve more than one order of magnitude improvement in along-track resolution compared to similar sidescan sonar systems at long ranges. Fig. 33 shows a SAS image compared with a sidescan sonar image. The object in the sonar images is a WWII submarine wreck at 200 m water depth outside Horten, Norway. Note the difference in resolution. Even though the SAS data is collected at longer range, and at much lower frequency, the image contains much more detail and fidelity, making it easier to determine the contents of the image. More details about SAS can be found in (Hansen, 2011).

Sidescan sonar and SAS imagery is used for detailed

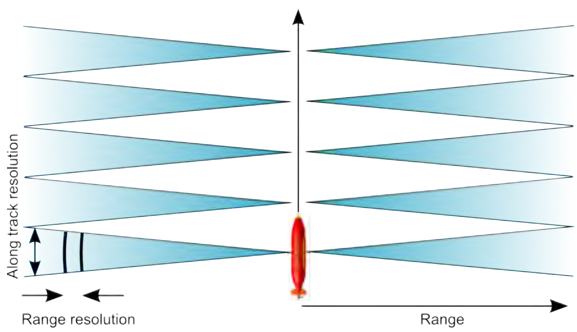

FIG. 30 Area coverage and resolution in sidescan sonar.

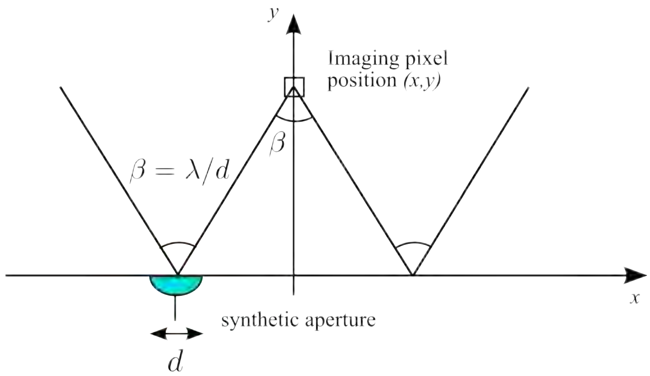

FIG. 32 Along-track resolution in synthetic aperture sonar.

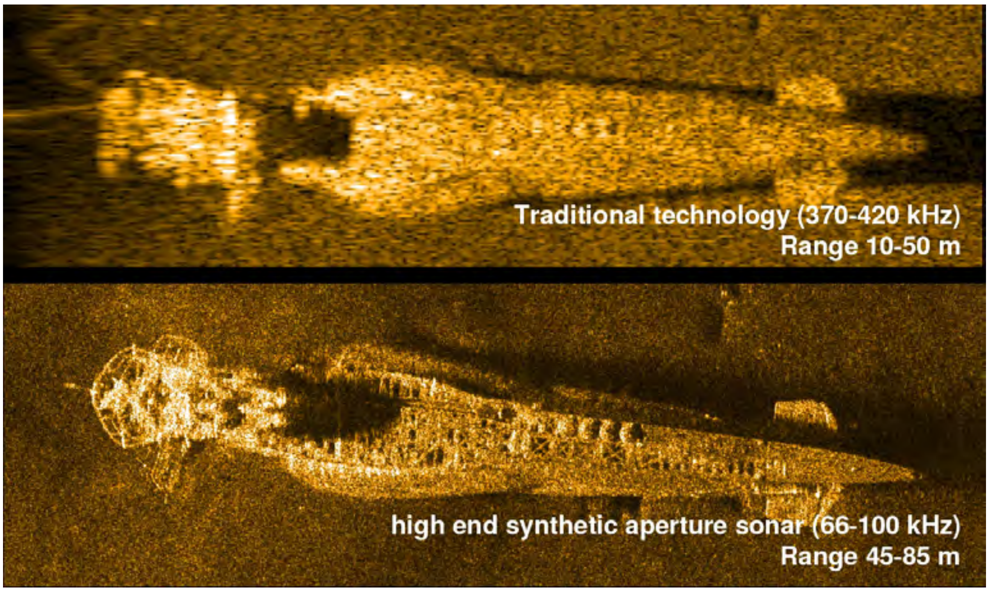

FIG. 33 Comparison of traditional sidescan sonar with synthetic aperture sonar. Images collected by HUGIN AUV. Courtesy of Kongsberg Maritime / FFI.

documentation of the seafloor. The properties and practical application of a sonar image, depicted in Fig. 34, is related to a number of factors: the imaging geometry will cause acoustic shadows from elevated objects on the seafloor; the image resolution and fidelity (signal to noise) is related to the ability to detect and resolve small objects; the water-seafloor interface and its relation to the acoustic frequency will affect the reflectivity for different bottom types.

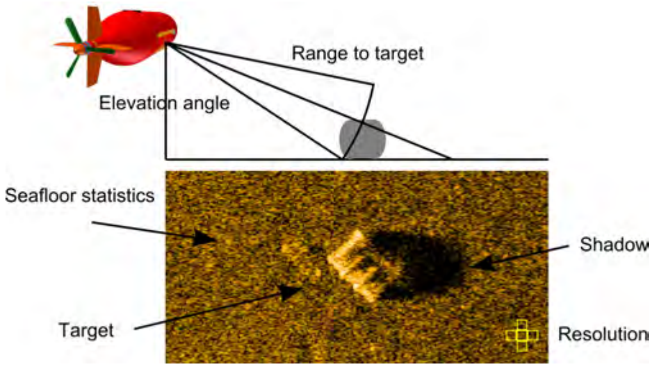

FIG. 34 Properties in a sonar image.

V. SUMMARY

Underwater acoustics is the only information carrier that can transport information over large distances in the ocean. The acoustic waves are affected by sound velocity variations with depth which cause refraction of the acoustic energy. The ocean is a lossy medium for acoustics. An acoustic wave can travel a fixed number of wavelengths, such that lower frequencies have longer range. The sonar principle is to locate an object by estimating the acoustic travel time and direction of arrival between sensor and object. Sonar imaging is estimation of backscattered acoustic energy in all directions and for all ranges. Typical sonar applications are: fish finding, imaging and mapping of the seafloor, military and navigation.

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