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NOISE POLLUTION OF THE SEAS

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INTRODUCTION

The exploitation of the seas is ever increasing. Commercial shipping, fisheries, offshore oil and gas production, exploitation of mineral resources, marine tourism, defence related operations, port construction, exploration, research activities etc. have shown increasing trends since WWII. Many ships operated today exceeds 100,000 to 150,000 tons, they are powered by engines having more than 120,000 hp and they are running at speeds exceeding 30 kts. Increasing size and speed lead among other things to increasing noise radiated into the sea. In general, the sea environment has become and is still becoming more noisy. Sometimes certain environmental protection oriented groups protest against selected transport or research activities like the Inuits against the proposed "Arctic Pilot Project" and the "Save the Whale" organization in the US against the ATOC project. Most frequently these protests are based on misunderstandings and lack of knowledge of the projects in question. However, we must realize that also the world under the surface of the seas has become more noisy over the past.

Also the action of a greater number of natural sources in the seas are contributing to the overall noise level on a site, the so-called **ambient noise level.** The ambient noise may be said to be **the residual noise background in the absence of any individual identifiable source** or that the ambient noise is the natural noise environment at a measurement site. The ambient noise level is the intensity, in dB, measured at a measurement site using a non-directional hydrophone and referred to the intensity of a plane wave having an rms pressure amplitude of 1 μPa. In spite of being measured in different frequency bands, ambient noise levels are always reduced to 1-Hz frequency band, and are then named the **ambient noise spectrum levels.** The ambient noise covers a very broad frequency range from below 1 Hz to several hundreds of kHz.

The ambient noise level on a site depends apart from the sources also on the oceanographic and geophysical conditions influencing the sound propagation in the environment at large around the site. Geographical locations have a decisive influence on the ambient noise level measured. Heavily trafficked shipping lanes, shalllow water coastal regions, busy ports etc. not only cause increased ambient noise levels in their nearest environments, but also at distances of up to 1000 km or more due to favorable sound propagation conditions. Several attempts have been made over the past to map the ambient noise as a function of frequency, identifying the major contributors to the noise. Early pioneering works on measurement and description of ambient noise were done during and after WWII by a group of acousticians headed by V.O Knudsen. Their measurements, in particular performed in shallow waters, covered the frequency range of 200 Hz to 50 kHz, and their results were published in 1948 [1] and are summarized in a series of curves known as "the Knudsen Curves". In particular the **wind** influence on the ambient noise levels were illuminated through the work of Knudsen et al. Later Ross [2] contributed to an improved understanding of the noise contribution from shipping, in particular in deep waters, where he showed that **shipping** is the dominant source of ambient noise in most ocean areas for frequencies from about 15 Hz to more than 300 Hz.

Apart from wind and shipping forming major sources of noise in the seas other natural and man-made sources of ambient noise are also active. The sources of ambient noise including their mechanisms and chacteristic features, their importance as contributors to the ambient noise levels, their frequency band and directivity, the significance of their geographical positions etc., will be the subject of this paper.

A. SOURCES OF AMBIENT NOISE

Sources of ambient noise to be discussed comprise: Tides and hydrostatic effects of waves, seismic activities, flow of sediments, turbulence, sea surface phenomena like surface waves and their breaking, nonlinear wave-wave interaction, bubbles, precipitation, biological activities, ice, thermal noise, shipping and other man-made sources.

1. Tides and hydrostatic effects of waves.

Tides and waves on the water surface cause hydrostatic pressure changes of a considerable amplitude at very low frequencies. The magnitude of the tidally produced pressure changes around a hydrophone in water may be demonstrated by the fact that a 1 meter increase in the water height will lead to an increase in pressure of 10^4 Pa, or to 200 dB re 1 μPa. As the tidal motion spectrum is represented by about 2 cycles/day, it is of minor interest in relation to ambient noise. Tidal motion may, however, influence ambient noise measurements through changes in the temperature of the hydrophone environment, which may lead to pyroelectric effects in the piezoelectric hydrophone materials and thus to false measurements, and through tidal currents, which can lead to flow induced vibrations of the hydrophone and its support.

Propagating surface waves are also sources of hydrostatic pressure changes in the sea. As the pressure amplitude falls off rapidly with increasing depth and with decreasing wavelength of the surface waves, the importance of surface waves as a source of hydrostatic pressure changes in deep water is low, while in shallow water a rough surface may have a dominating influence on pressure-sensitive hydrophones at low frequencies.

2. Seismic activities

Due to the fact that the earth is in a constant state of seismic activity, earth unrest is causing low-frequency sound in the sea. Seismic activities range from contributions from large-scale intermittent sources like individual earthquakes (seaquakes) and distant volcanic eruptions to microseisms. Microseisms having a nearly regular periodicity of 1/7 Hz and a vertical amplitude of 10^{-6} m will lead to a pressure amplitude in the sea of 120 dB re 1 μPa [3]. Seismic unrest may also be found at frequencies above 10 Hz.

Also contributions from man-made activities like industrial plants, road transport, construction work etc. in coastal areas may, as seismic waves, propagate into shallow water areas close to the shore.

More than eighty years ago Wiechert [4] proposed a close relation to exist between microseisms and ocean wave activity. In spite of the fact that several other mechanisms also have been proposed to account for the general microseisms, the most favoured mechanisms are nonlinear interactions between surface waves.

Noise related to ocean microseisms dominates acoustic spectra at frequencies below 4 - 5 Hz. Ocean surface waves travelling in opposite directions in the vicinity of a storm or as a result of a reflection from a coast can generate a standing wave field. Unlike progressive surface waves, for which the pressure effects decay exponentially with depth, a standing surface wave field produces a mean second-order pressure effect at twice the frequency of the surface waves that is unattenuated with the depth. The pressure amplitude produced by nonlinear surface wave interactions is proportional to the amplitude product of the interacting waves.

3. Turbulence

Deep water turbulence has been proposed [5] as a source of low-frequency noise. The irregular and random motion of the water in turbulent currents of large or small scales is able to produce underwater noise. The pressure changes associated with the turbulence may be radiated far from the turbulent region and will appear as a part of the ambient noise. However, the noise as such radiated from the turbulent region is not likely to be of significance due to its quadrupole character and thus its rapid fall-off with distance from the source region. A pressure sensitive hydrophone may, however, pick up the turbulent pressure when measurements are performed in the turbulent region. Pressure levels between 115 and 150 dB re 1 μPa related to flow velocities between 0.02 and 0.3 m/s have been suggested [5].

Low-frequency underwater noise may also be produced by turbulent pressure fluctuations in the **atmosphere** near the ocean surface [6, 7]. The induced noise field is related on a 1:1 frequency basis, with the fluctuations in the existing turbulence field. It is concluded in [7] that atmospheric turbulence is the dominating source of wind generated noise above 5 Hz. Experimental results covering the frequency range below 10 Hz are, however, sparse, in particular due to experimental difficulties related to hydrophone installations; too short time periods of measurements done and the use of local test sites with too limited environmental data available.

4. Surface phenomena

It has been demonstrated at many occasions that low-frequency underwater sound is dependent on the **wind speed** for both deep and shallow water. The Knudsen spectra based on many observations gave relations between sea state or wind force and the level of underwater ambient noise. The frequency range over which wind speed via various noise producing mechanisms have an influence on underwater ambient noise is very broad. Local wind speed is the dominant factor controlling wind/wave noise for frequencies above about 500 Hz, while distant wind dominated sources may contribute essentially at frequencies from 10 Hz to near 500 Hz.

Apart from the fluctuating forces exerted on the sea surface due to the wind's turbulence, as discussed above, wind blowing over a rough surface may also generate sound which penetrates into the water [8].

Spectrum levels in the frequency range from 8.4 Hz to 3 kHz were studied by Piggott [9] in shallow water on the Scotian Shelf off Nova Scotia. For most of the data in [9] the noise spectrum level L(f) at a frequency f was found to be related to the wind speed V in miles per hour by the expression:

$$L(f) = A(f) + 20\, n(f) \log V \tag{1}$$

where A(f) is a frequency dependent threshold level, n(f) = 2.1 for frequencies below 50 Hz and n(f) = 1.2 for frequencies from 400 to 2000 Hz. These results show, that the sound pressure level is approximately proportional to the square of the wind speed below 50 Hz. As the wind speed dependent noise possesses a seasonal effect in shallow water, A(f) in Eq. (1) varies by 3.5 dB from winter to summer. In general, shallow water, wind-generated noise and its characteristics, are highly variable and rather difficult to predict.

All surface phenomena leading to low-frequency ambient noise in the sea are more or less related to the influence of the wind. This also concerns the sound sources connected with (1) breaking of waves, (2) nonlinear wave-wave interaction and (3) bubbles.

4.1. Breaking of waves

Wave breaking is a widespread phenomenon on the wind-driven sea surface, occurring over a wide range of length scales and appearing to play a major role in surface layer mixing and in underwater ambient noise generation. However, which mechanisms within the breaking waves, which actually generate the sound, are not yet fully known.

On a large scale, the most common type of wave breaking process is related to the **spilling breaker**, which can be induced by steady flow over an obstacle. These breakers tend to entrain air bubbles at the lower end of the "roller". Among the progressive waves, another wave breaking type is characterized by the occurrence of **plunging breakers**. Plunging breakers will, before their short plunging state, demonstrate a bend-over cusp shape with jetting fingers along the leading edge. These fingers develop into streaks which appear to lengthen and ultimately to collapse into a violent moving region of bubbles and water along the leading edge. According to [10] the first detected sound should occur with the appearance of an air-water cloud (bubble cloud) pushed ahead by the waves. The sound level produced should also increase with the increasing size of the air-water cloud. The final stage of the breaker shows several foam lines produced in succession, each probably associated with a burst of sound. The produced sound level gradually decreases with these foam lines and a turbulent pool is left behind the wave. In a mixed sea, characterized by short surface waves riding on longer waves, the orbital compression by the long waves compels the short waves to steepen and to break near the long wave crests [12, 13].

There is currently no clear criterion to indicate when a wave will break or that a wave will develop into a spilling or to a plunging breaker. The general breaker at sea will posess characteristics of both. Moreover, visual observations suggest that vigorously plunging breakers are in fact quite rare [11]. Typical fetch-limited breaking waves inject bubbles to depths typically 20 - 30 cm and thus too shallow to be associated with an ordinary plunging breaker.

Standing waves break in a different manner [14]. The crests can become unstable, throwing droplets into the air, or overturning symmetrically on either side. In extreme cases the trough of the wave collapse, throwing up a water jet of high velocity.

Prior to wave breaking, low-frequency sound in the frequency range from 2 to 200 Hz may be generated by the interaction between surface waves and turbulence, this being the case for sea states low enough that breaking of waves do not occur [15].

4.2. Nonlinear wave-wave interaction

Nonlinear interaction between ocean waves has been of interest, not only to seismologists as mentioned above, but also to the oceanographers due to the fact that this interaction mechanism most probably leads to a self-stabilization of the ocean wave spectrum. The second-order effect involved in the surface wave motion by two waves progressing in opposite directions and thereby forming a standing wave, has been demonstrated to be the dominant mechanism of noise generated in the frequency range from 0.1 to 5 Hz [16]. Experimental evidence in [16] shows that the greatest wind related noise levels occur when a 180° shift in the direction of the wind of long duration brings a growing sea into direct opposition with the one already established. While the two wave fields interact, the underwater low-frequency noise level remains very high, but it drops rather fast to a level some 20 dB lower as the new wave field becomes dominant, thus reflecting the nonlinear wave-wave interaction process influence on the underwater noise level.

Above 1 Hz the spectrum of ambient noise measured near the seabed of deep seas tend to show a consistent increase of 8 to 10 dB per octave towards the lower end. Recent experimental studies [17] in deep seas have shown that seismic interface-wave components exists beyond the frequency range predicted by classic elastic waveguide theory, and that these components dominate the seafloor noise field. The character of water-saturated marine sediments and scattering by rough elastic surfaces [18 - 21] support the idea that in spite of the much greater distance to the sea surface in deep water, a coupling like in shallow water of surface radiated infrasonic noise into seismic waves through modal matching in either the propagating or evanescent wave spectrum part is possible. A reliable theory has recently been developed [22] for the fact that interface roughnesses provide the critical mechanism for excitation of Scholte waves in both shallow and deep sea environments.

4.3 Bubbles

Surface waves breaking in deep and shallow water produce **clouds of bubbles** which persist below the sea surface as identifiable acoustic targets for periods of several minutes.

They are carried and dispersed by the near surface turbulence, and may serve to identify fluid regions directly affected by the breaking waves which produce them. The distribution of the bubble clouds after their formation is a function of the properties of the bubbles themselves as well as of the turbulence. Apart from breaking of waves, bubble clouds in the uppermost layer of the ocean may also be produced by precipitation, break-down of organic materials, and ship traffic, where bubbles in wakes may persist for hours. Beside the obvious acoustic influence from the bubble clouds, they play an important role in the air-sea interaction processes as for instance in the exchange of gas, in production of sea salt aerosols, in electrical charge exchange and in chemical fractioning in addition to the net upward flux of organic materials and bacteria [23].

Observations over the past have shown that the size distribution of bubbles after normalization by depth and wind dependence, follows a power law dependency on radius. Estimates of the slope with increasing bubble radius vary from -3.5 to -5 [24, 25]. The number of bubbles also decreases with the depth z, approximately as $\exp(-zk^{-1})$, where k is some scaling length. As shown in [26] the total number of bubbles increases very rapidly with the wind speed U_{10} (measured at 10 m height above the sea surface). A relation showing as rapid an increase as $(U_{10})^{4.5}$ has been suggested. The bubbles present near the sea surface resonate over a broad frequency range.

A rough estimate of the natural frequency of the bubble oscillations is given by expression (2):

$$\omega_o = R_o^{-1} \left[\frac{3\gamma p_\infty}{\rho}\right]^{1/2} \tag{2}$$

where R_o is the equilibrium radius of a bubble and where ω_o is the angular frequency in the bubble vibration. From Eq. (2) a natural frequency of 100 Hz may be ascribed to a bubble having a radius of about 0.03 m. As most bubbles produced near the sea surface are much smaller, the individual bubble contribution to the low-frequency noise level in the sea is small. However, the collective oscillations of the bubbles in the bubble cloud near the sea surface may generate low-frequency sound. It is well-known, that a small amount of bubbles in water significantly changes the bulk compressibility of the water, while not drastically changing the density. These changes lead to a considerable variation in the speed of sound in the bubble-water mixture [27 - 29].

For a volume fraction of air in water of 1 ppm the sound speed in the water-air mixture C_m will be about 320 m/s. If a bubble cloud in water is assumed to have a linear dimension L, this cloud may be considered as a system of coupled oscillators with the frequency of the lowest mode given by:

$$f_o = \frac{C_m}{L} \tag{3}$$

which for naturally occurring values of L may lead to rather low frequencies [31 - 38].

As mentioned earlier, turbulence generated noise in pure water is of quadrupole character and turbulence is, therefore, forming a very weak source of sound. The presence of bubbles will, however, amplify the turbulence produced noise by conferring to it a monopole nature. The magnitude of this intensity amplification can be estimated to be of the order of (C_w^4/C_m^4), where C_w is the speed of sound in water [30]. In this way, through the presence of bubbles, turbulence can contribute a significant amount of ambient noise up to frequencies of the order of several tens of Hz.

5. PRECIPITATION

In particular **rain**, but also **hail** and **snow**, falling on a sea surface have turned out to be considerable contributors to the ambient noise level in the sea. The underwater sound spectrum generated by rain has frequently a shape which can be distinguished from other sources of sound in the sea, and the relationship between the spectral levels and the rainfall may be quantified. Rainfall is a climatic factor of great importance and, therefore, measurement of rainfall has a high priority. However, it has been estimated that about 80% of the Earth's precipitation occurs over the ocean where the smallest number of weather stations are located. Measurements of underwater sound have, therefore, been proposed as a way for determination of the amount of rain falling on the sea surface [39]. A prospective future procedure for rainfall measurements could include underwater ambient noise measurements at certain geographical locations combined with the use of satellite observations and the use of weather radar. However, there still appears to be a long way to this goal. Several attempts to describe the underwater noise spectra produced by rainfalls of various magnitudes have been made over the years [40 - 44], but a considerable deviation did exist between rain noise data produced by various scientists.

Possible sources of underwater sound caused by **single droplets** of rain are the transient introduction of the droplet into the water, the secondary splashes thrown up by the entry, oscillations of air bubbles trapped near the surface and oscillations of cavities open to the atmosphere.

The individual contributions to the underwater noise spectrum from these mechanisms are strongly influenced by factors related to the droplet size, shape and movement before it hits the water surface. Among these factors shall in particular be emphasized: The equivalent raindrop diameter, the size distribution of the raindrops, the shape of the raindrops, the wind velocity and its profile, surface tension and raindrop temperature, and, frequently, the conditions under which the measurements took place [45]. Underwater sound generated by **multiple raindrop impacts** on a water surface will be influenced by the interaction between the individual impacts, which will comprise water droplets falling on a not-plane (random shape) water surface, drops falling in and out of phase leading to phase cancellation, resonance etc. The noise generated by multiple raindrop impacts is possibly the field of rain noise generation where most research is still needed. Not only extensive experimental studies have to be performed, but a theoretical (numerical) basis has also to be established. Experimental evidence has been created for the strong influence of **surface tension** on the noise level produced by **real rain** (multiple impacts) [46-49]. The results show, that a considerable part of the noise produced by raindrops falling on a sea surface is caused by the pulsation of bubbles trapped near the surface. For instance, the characteristic spectral amplitude of rain noise around 14 kHz is caused by formation and pulsations of small bubbles produced by raindrops having a diameter between 0.8 and 1.1 mm. These bubbles are formed near the water surface by closure of cavities produced by impact of raindrops and under the influence of the surface tension. Only raindrops in the size range mentioned above are leading to bubble formation at all impacts. By adding small amounts of detergents to water, thus reducing the surface tension, a very remarkable reduction in the rain noise took place and the characteristic spectral amplitude around 14 kHz disappeared [50].

6. Biological activities

Biological noise sources are many and varied. The frequency range of the various biological sounds is very wide, from about 20 Hz to more than 300 kHz. The principal sources of low-frequency biological sound are marine mammals, mainly whales and porpoises [51]. Some of the sounds generated are used for echo-location, for detection of food, and for communication between the species, but the functions of many sounds are not known. Naturally, because of their biological origin, such sounds have diurnal and seasonal cycles. Groups of mammals such as whales can generate such loud, continous sounds as to raise the ambient noise level significantly.

Some peculiar transient sounds have been heard with low-frequency hydrophones over widespread areas of the Atlantic and the Pacific Oceans [52]. These sounds are supposed to be produced by the finback whale, and consist of a regularly pulsed **20 Hz tone** of about one second duration at intervals of several times per minute. By triangulation, the sources have been tracked and found to travel meandering paths with speeds from 2 - 4 knots. The total radiated acoustic power of a single pulse has been estimated to lie between 1 and 25 Watts, assuming an omnidirectional source. Seasonal changes in the "20 Hz noise" are quite pronounced [53].
Of the approximately 2000 species of deep-sea fish, only the benthopelagic, which swin near the bottom have both the swimbladder and drumming muscles required to produce loud low-frequency sounds [54]. The noisiest shallow-water fish includes toad fish, croakers and catfish, and their biological noise is quite often produced at dawn or in the evening.

In most shallow waters there is a general background of biological noise, but the most pronounced effect is due to the choruses that result when a great number of animals are calling at the same time. Such choruses cover various parts of the spectrum and they typically increase the spectrum levels by 20 dB or more. The choruses may be considered to belong to two general categories. The first category is the diurnally varying type of chorus which occurs for a few hours per day at approximately the same time of the day. The evening chorus occurring for a few hours after sunset is the prevailing. However, similar choruses are sometimes observed near sunrise and occasionally at other times of the day. The other type of chorus sounds result from fish and are often related to their spawning. These, less predictable choruses, may occur for longer periods of the day and they often have pronounced seasonal relations, which differ considerably between the species. Many fish use their gas-filled swim bladder and their drumming muscles to generate sound, thus being able to produce a considerable sound pressure level.

7. Ice Noise
Underwater noise **under the ice** differs both in level and in characteristics from that measured in open-water conditions. Noise under the ice is a superposition of a large

number of independent noise events, each presumably caused by **ice fractures** of one or another kind. Ice can be fractured by overthrusting and consequent flexural straining in response to horizontal internal ice stresses. But ice can also be fractured by turning moments on pressure ridges in response to opposing wind and current stresses [55]. Acoustical radiation caused by such fractures produced by local ice motion is supposed to lie, at least partially, in the frequency range of 1 to 300 Hz. The noise has been found to be spiky and impulsive when the air temperature decreases and tensile fractures are formed in solid, shore-fast ice. However, under rising temperatures, the spiky character of the noise disappears and a more Gaussian like amplitude distribution is found [56].

The impulsive, non-Gaussian character of Arctic ambient noise is different from open ocean noise. Noise fluctuations between 10 - 20 dB on time scales of hours are quite common in the central Arctic. The average spectral shape shows a peak at about 20 Hz and then a monotonic decay up to several kHZ [57].

Measurements performed near the compact ice edge shows a noise level about 12 dB higher than in open waters, and about 20 dB higher than the level far from the ice fields. Ambient noise in the marginal ice zone is quite different from open oceans as well as pack ice covered oceans. The combination of individual ice floes and open water permits an interaction of wind and surface gravity waves with the ice floes, causing flexural failure of the ice floes and floe-floe interaction to contribute to the noise level.

Also **vibration** of the ice may produce low-frequency sound. Wind blowing over the rough ice surface becomes turbulet and transmits varying pressures to the ice and through it, to the water. Wind produced sound is more prominent under a non-continuous ice cover than under a continuous one. Vertical ice motions measured with seismometers mounted on the ice generally correlate with ambient noise levels at 60 m depth at 50 Hz [59]. Another type of noise due to the ice motion is an almost sinusoidal signal at 7 Hz and a variable amplitude, which is attributed to standing wave patterns between the surface and the seabed [60].

As icebergs melt in warmer waters, **entrapped air bubbles** are released which oscillate or collapse generating noise [61]. The air pressure in the bubbles trapped in glacier ice is substantial and may exceed 2 MPa. Larger bubbles released, or formed by merging of several smaller bubbles into larger bubbles, may lead to sound generation at low frequencies.

8. Shipping

A major source of underwater ambient noise primarily in the frequency range of 10 to 500 Hz, is shipping. **Distant ship traffic** is a principal source of low-frequency noise in the range of 20 to 150 Hz. Such traffic may take place at distances up to 1000 km or more, thus competing with **distant storms** as sources of low-frequency noise [2]. Even if ship traffic generates sound over a broad frequency band, the propagation over distances of several hundreds of km or more will attenuate sound at higher frequencies, and only low-frequency sound will be received from distant shipping. This also means, that the spectral composition of the sound received from ship traffic at short distances will be different from sound produced by distant shipping.

The acoustic power produced by a ship is only a small fraction (frequently less than 1/1,000,000) of the mechanical power used for moving the ship. A modern submarine proceeding at slow speed produces on the order of 10 mW acoustic power, while surface ships generally radiate from 5 to 100 W of acoustic power [2]. Since each ship is operated in a wide variety of configurations from unloaded to fully loaded, at various speeds and in varying mechanical conditions, the sound generated by a ship can vary over a wide frequency band. As a handrule from 0.3 to 5 W of acoustic power is radiated by a ship for each MW of mechanical power of the ship's machinery.

The increasing number of ships at sea due to more efficient port handling facilities, the increased size of the ships including increased machinery power, and the increased speed of the ships contribute to an increased ambient noise level in the seas. The world's population of larger ships consists of about 20% tankers, nearly 70% cargo ships and about 10% of passerger/ferry ships. The increasing container transport contributes to an increase in the number of cargo ships. A more than 25 dB higher general ambient noise level in busy shipping lanes compared to the noise level far from the lanes is a reality. Shipping noise is the major contributor to ambient noise in a number of geographical locations. In particular near a number of ports, where also a dependence of the ambient noise level on time during the day is observed. A 6 - 8 dB higher noise level is measured during certain periods of high activity compared to periods of low activity. It is, therefore, not remarkable if the general ambient noise level due to ships has increased 12 - 15 dB since WWII, in some locations even more.

The principal sources of radiated sound from ships are: (1) the propulsion system; (2) the propeller; (3) the auxiliary machinery; (4) the hydrodynamic effects and (5) the hull movements. Three types of power plants are now commonly used in merchant ships: (1) Geared steam turbines; (2) direct-drive, slow-speed diesels and

(3) geared medium-speed diesels. Of these direct-drive, slow-speed diesel constitute about 2/3 of all ships at sea and in particular ships operating in shallow water areas. Steam turbine driven ships constitute about 25% of the ships at sea. The **propulsion system** contains in general large rotating shafts, gears, bearing and depending on the ship type, reciprocating engines, turbines, or electric drive motors. A small unbalance in one of these devices results in oscillating forces which are transmitted through the machine structure, the foundations and the hull, to the water. An amplification due to structural resonances may take place along this transmission line. The acoustic signals generated in this way are normally narrowband tonals at the systems rotational frequencies and their harmonics. Broadband signals in the propulsion system are for instance generated by friction forces.

The dominant sources of surface-ship radiated noise are **propeller cavitation** and propeller singing. It is estimated that 80 - 85% of the noise power radiated into the water by surface ships comes from the propeller cavitation. There are two types of radiation from cavitating propellers, low frequency tonals and a broad continuum [2, 62]. The tonals are radiated up to the first 10 harmonics of the blade frequency and are usually dominating for frequencies below about 40 to 50 Hz. The continuum controls the spectrum above 50 Hz, generally peaking between 50 and 150 Hz. Above 150 Hz, the spectrum decreases with frequency at about 6 dB per octave. Both the tonals and the continuum are modulated at the shaft rotational frequency, and the continuum is even more strongly modulated at the blade frequency. Cavitation, i.e. stable and transient, may form in the low-pressure regions on the propeller blades as surface cavitation or as tip-vortex cavitation. Because the onset of cavitation is related to ambient pressure as well as to the speed of the propeller, cavitation noise decreases with depth and increases with speed. Also the shape of the propeller blades has a strong influence on the onset of the cavitation, and even small variations in geometry may separate propellers with and without cavitation. While cavitation noise is a major component of the noise signature of surface ships and of submarines operating close to the sea surface, submarines travelling at sufficient depths may avoid propeller cavitation.

In addition to propeller cavitation noise, tonal components may be produced by vibrational excitations of the propeller blades by the stratified flow in the wake of the ship. The occurrence of **singing propellers** is visible as spectral lines in the noise spectra. Also amplitude modulations of the cavitation spectra at the propeller blade rate may frequently be found to characterize certain ship types and their propellers.

Auxiliary machinery like pumps, blowers, electrical generators etc. will primarily produce tonal components due to dynamic unbalances in rotating components. As these devices normally are operating at constant speed, the sound produced is, in general, relatively stable in amplitude and frequency.

The **hydrodynamic noise sources** also include cavitation produced along the ships hull, in valves, in pipe bends, in hydraulic machinery etc. This broadband noise is transmitted through machine structures, along pipes, through bulkheads and sea valves into the water. Water flow past struts may induce structural vibrations through processes of unbalanced vortex shedding off the trailing edge of a strut. These vibrations radiate sound into the sea. Turbulent flow along the hull structure may couple pressure fluctuations back to the hull, thus producing vibrations and sound radiation.

Low-frequency sound radiation from **hull motions** may involve the whole hull. The hull may experience a rigid-body motion in which it retains its shape and either vibrates in position in response to an external alternating force, or rotates about an axis. Moreover, the hull may vibrate in a beam-like flexural mode (whipping) and it may vibrate in a dominantly longitudinal mode, in which the two ends move out of phase in an accordionlike motion. At somewhat higher frequencies, but still below 300 Hz, whole compartments may resonate and emit sound as s cylindrical shell vibrating in a rigid cylindrical baffle. Low-frequency radiation from hull structures is much more important for submerged vehicles, for which the image cancellation, as found for surface ships, is much reduced and for which the propeller cavitation may be absent.

9. Other Man-Made Sources

In recent years, a new, major, low-frequency source in shallow waters has raised the ambient noise levels below 100 Hz, occasionally by as much as 20 dB. The source is the explosion-like pulses used during seismic surveying and produced by boomers, air guns, underwater explosions etc. These sources cover a broad frequency range, but with a considerable acoustic power situated at low frequencies. One seismic profiler may transmit the same acoustic power into ambient noise as nearly 300 merchant ships together. Moreover, the significance of off-shore oil exploration as a source of ambient noise is enhanced by the fact that locations on the shallow water parts of the continental shelf for such activities are often optimum for propagation of sound to distant receivers. Drilling, communication and transport activities related to off-shore work produce sound having some of the same features as shipping [63, 64].

The use of **underwater explosions** and other high-intensity sound sources involve bubble pulsations at low frequencies, but of high intensities. Depending on the depth of the explosion, from 10% to 50% of the energy available in the explosive is radiated as sound [65]. Also boomers and electrical discharges over a spark gap contribute low-frequency sound, in particular due to bubble formation or exitation [66].

Also long range underwater communication and tomographic research contribute - on a minor scale - to the ambient noise level. The Heard Island Feasibility Test source transmitted a signal at 209 - 220 dB re 1 μPa at a depth of 175 m (position of the communication channel). The signal was centered around 57 Hz with a max. bandwidth of 30 Hz [67]. The acoustic power transmitted was about 3.3 kW. This project is now being continued in the ATOC studies.

10. Sediment-Generated Noise

Interparticle collision of mobile seabed materials influenced by flow near the seabed, where the highest concentration of suspended sediments is found, may lead to contributions to a wideband ambient noise spectrum around 10 kHz [68]. Experimental data show that an ambient noise level of approximately 70 dB re 1 μPa $Hz^{-½}$ may be obtained. The experiments were performed over a seabed consisting of quartz sand overlain with gravel and the flow was caused by strong tidal currents [69].

11. Thermal Noise

At elevated frequencies, i.e. above 100 kHz the thermal noise becomes of importance as a major part of underwater ambient noise. As shown by Mellen [70], the thermal noise of the molecules of the sea places a limit on hydrophone sensitivity at high frequencies. The equivalent noise spectrum level at ordinary sea temperatures produced by thermal noise may be expressed as:

$$NL = -15 + 20 \log f \quad (dB\ re\ 1\ \mu Pa) \tag{4}$$

where f is the frequency in kHz. The noise is increasing with frequency at a rate of 6 dB/octave and it leads to a frequency dependent threshold for the minimum observable sound pressure level in the oceans.

B. SPECTRA OF AMBIENT NOISE

The broad variety of sources of ambient noise in the sea discussed above leads to a broad noise spectrum. The most prevailing sources are shipping and wind, while the other sources may be of major importance, individually or together, at certain locations or at certain timers. Moreover, most sources are related to the sea surface. The discussion of spectra of ambient noise may appropriately be divided

into (1) **deep-water ambient noise spectra** and (2) **shallow-water ambient noise spectra.**
Due to the influence of attenuation on the noise (attenuation caused by divergence, absorption and scattering), the noise spectra may be divided into three distinct frequency regimes. The high-frequency regime is defined as that for which the attenuation is so high that only the closest intersection of the sound rays with the sea surface contributes significantly. In shallow waters, this regime includes frequencies above 10 kHz, however, in deep waters, the high-frequency regime applies down to about 1 kHz. For deep waters the low-frequency regime may be devided into two parts. Below about 150 Hz, the attenuation may be so low that it no longer controls the ocean area contributing to the ambient noise level on a measurement site. At these low frequencies even sources located at the edges of the ocean basin may make significant contribusions to the ambient noise level. Therefore, the 3 frequency regimes to be considered when analyzing deep-water ambient noise are: (1) Below 150 Hz (Influence of the whole ocean basin); (2) 150 to 1000 Hz (Influence of numerous surface zones) and (3) above 1 kHz (Influence of the local surface dominates).

1. Deep-water ambient noise spectra
The deep-water spectrum may be divided into 5 regions, depending on the prevailing surces of noise. Region I, for frequencies up to 1 hz, is still not totally explored. The sources are assumed to be of hydrostatic and seismic origin. Measurements to be performed at the very low frequencies places strict demands to the equipment as many sources of errors may influence the results, as for instance "self noise" caused by flow around the hydrophone and its supporting structure. Also in region II, from 1 to 20 Hz, measurement difficulties may influence the results. This frequency region is characterized by a spectral slope of -8 to -10 dB/octave. The most probable source of noise in this region is turbulence and shipping, while the wind influence is small. In region III, from 20 to 500 Hz, the ambient noise spectrum flattens out and forms a plateau. This frequency region is mostly dominated by shipping and off-shore noise. In particular noise from distant shipping and off-shore activities on the continental shelf will contribute to the level and the directivity of the ambient noise in deep water in region III. The spectrum level in region III is strongly influenced by the degree of shipping in the area where measurements take place.

Region IV, ranging from 500 Hz to 50 kHz, is the original Knudsen spectra region. In this region the spectral curves have a slope of -5 to -6 dB/octave, and the major sources of noise are wind controlled activities at the sea surface (local sources). A variation in the noise level of more than 30 dB depending on the wind speed is found in region IV. Region V, comprising frequencies above 50 kHz, is dominated by thermal noise, originating in molecular motions of the sea. This region shows an increase in the spectrum level of 6 dB/octave.

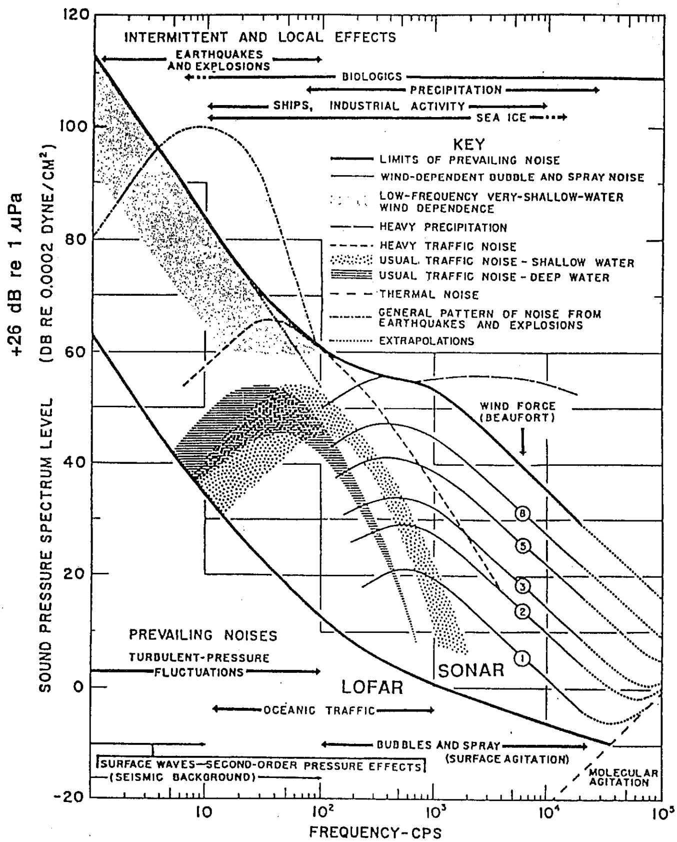

Figure 1. Ambient noise spectrum levels as a function of frequency.

2. Shallow-water ambient noise spectra

While the spectra of ambient noise measured at deep waters are relatively well-defined without too great variations from time to time and from place to place, this is not the case for shallow-water ambient noise spectra. Here, location and time have a considerable influence on the spectral composition due to the interaction between noise contributions coming from a broad variety of sources. The ambient noise levels and spectra show considerable differences when measured at various coastal regions or when measured in bays and harbours. The most active sources in shallow water are: (1) Shipping and industrial activities, (2) wind effects and (3) biological noise. Also intermittent sources like precipitation may have a strong influence. In shallow waters, however, the influence of distant shipping on the noise level is very small due to the shielding effect caused for instance by the "stripping" of modes by sound propagating up-slope from deep to shallow waters. Figure 1 shows the contributions to ambient noise in the sea as a function of frequency, arising from various sources.

C. DIRECTIVITY OF AMBIENT NOISE

The directivity of ambient noise is in particular influenced by the propagation conditions in the sea. As a rule of thumb, low-frequency noise originated at great distances arrives at a hydrophone via primarily horizontal paths, whereas high-frequency noise originates at the sea surface and arrives at the hydrophone at closer to vertical directions.

Over broad regions of ambient noise spectra the sources related to activities at the surface of the sea are the most important. Only at very low frequencies seismic effects turbulence and hydrostatic effects are prevailing. The measurements of ambient noise directivity has, therefore, in particular taken place at frequencies above 20 Hz, where surface sources and distant shipping, storms etc. influence the deep water spectra.

The sea surface is a pressure-release surface, and, therefore, the basic pressure radiation pattern from a near-surface source is a cosine function having its maximum straight down and a zero in the horizontal direction. For sea-surface radiation a function of the form:

$$I(\theta) = I_0 \cos^m\theta \tag{5}$$

where I_0 is the intensity radiated by a small area of the sea surface in the downward direction (θ = 0), and where m is an integer. Most measurements have confirmed a value of m = 2, indicating the dipole character of the radiation (m = 0, denotes the monopole). If the sea surface was flat, and therefore a perfect pressure-release reflector, the zero would be very deep due to perfect cancellation of the direct and the surface-reflected paths. However, the sea is usually rough, and the cosine pattern approaches a minimum rather than going to zero [12]. Incomplete knowledge about the surface decoupling effect at near-grazing angles for a rough surface limits the possibility of modelling sea surface generated ambient noise.

A study of the vertical structure of the ambient noise arrivals at a measurement location may be based on an examination of the contribution to the total noise power arriving in a number of vertical sectors. The surface sources that contribute noise to a particular vertical sector are those located where the ray bundle from the receiver in the direction of the limiting rays for the sector intersects the sea surface. It is important to realize that the same ray bundle may intersect the surface in several places. Noise received at each angle comes from distributred surface sources located in each of the zones where the ray paths intersect the surface. How many zones to be involved depends on the attenuation of the noise, but a general rule of thumb is, that all zones must be considered out to distances for which the frequency-dependent absorption loss becomes dominant.

The **coastal enhancement effect** may influence the ambient noise level in deep waters. The mechanism behind the coastal enhancement effect is angle transformation for the propagating noise by reflection from outwardly sloping bottoms. This transformation is shown in figure 2 where sound rays from a source in shallow water (on the continental shelf) propagate out into the deep basin. The importance of the coastal enhancement effect for low-frequency ambient noise stems from the fact, that there are places where shipping lanes converge over shallow sloping bottoms like for instance the Straits of Gibraltar, the southwestern approaches to the English Channel etc. Noises from these areas often dominate the low-frequency spectra for receivers located in the deep sound channel. The coastal enhancement effect may not only explain the vertical arrival structure measured in the seas, but it may also explain features of the horizontal arrival structure. Figure 3 shows an example on the horizontal directionality of ambient noise.

The strong variation in ambient noise with location, and thus with the environmental conditions on the measurement site, has led to the idea that transmission loss can be determined from differences in the ambient noise spectrum levels at various positions in the sea [72]. Most recently, an exciting application of the ambient noise has been suggested [73] comprising the use of the local ambient noise as the signal for probing the seabed and for detection of objects in the water column and on the seabed. Experimental results have in a convincing way [74] confirmed the applicability of ambient noise for underwater acoustical studies by exploitation of the concept of "Acoustical Daylight", and advanced ambient noise imaging systems are now being built [75].

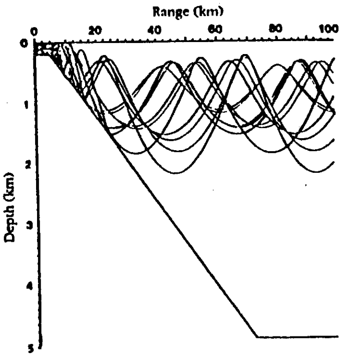

Figure 2.
The coastal enhancement effect. [71]

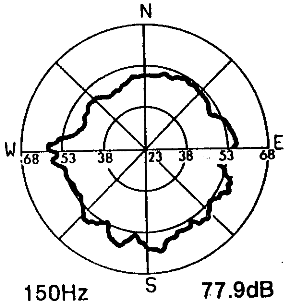

Figure 3.
Example on horizontal directionality of ambient noise

D. CONCLUSIONS

A general fact seem to be that the average ambient noise level in the seas has increased with 12 - 15 dB since WWII. The major contributor to this increase is the man-made contribution, while the contributions from the natural sources is about unchanged. The consequences of the increased noise level are still more or less unknown, and comprehensive and detailed research involving scientists with different educational background is strongly needed. In particular a study of the influence of noise on life in the seas is most necessary. Some more recent observations have shown that fish in the Nordsee gathers in schools on positions near the off-shore oil and gas producing platforms, which form some of the most noisy places with broadband continuous as well as transient noise. That fishing is prohibited near the platforms shall only be mentioned. The use of new high-resolution multibeam echo sounders which permits to observe the fish schools over broad angles, and not only in the vertical direction, has shown that certain types of fish, not as earlier assumed, are unaffected by the noise produced by the fishing vessels, but they try to escape to the side. Moreover, the comprehensive studies of the reaction of sea mammals to the high-power sound produced by the Heard Island Feasibility Test [67] and the later ATOC experiments have shown that certain types of sea mammals are influenced, while other show no reaction to the low-frequency signals transmitted. Observations have, moreover, shown that the about 20 Hz signals emitted by the whales in their communication and navigation is still emitted with same signal-to-noise ratio as it was, when it was first identified in the 1950s. The whales have apparently adjusted themselves to the new noise level and raised their voice much as humans are doing in order to adapt to cocktail party noise. This flexibility shown by some of the inhabitants of the seas is maybe exceptionel. Only more research will be able to tell us if the increasing ambient noise level of the seas form a pollution with short or long term damages to the life in the sea. The consequences of the chemical and biological pollution of the seas are obvious. What are the consequences of the noise pollution?

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